Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [Visible Light Communication : Tutorial]

Date Submitted: [9 March 2008]

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Re: []

Abstract: [The overview of the visible light communication (VLC), application scenarios and demonstrations in the various are presented in this document. The research issues, which should be discussed in the near future, also are presented.]

Purpose: [Tutorial to IEEE 802.15]

Visible Light Communication

- Tutorial -

2008. 03. 17

Samsung Electronics
University of Oxford
ETRI

Outline

- Part 1 (Samsung)
  - VLC introduction
  - LED introduction
  - VLC potential application
- Part 2 (Oxford Univ.)
  - VLC components
  - Technical challenges

VLC introduction

- **VLC (Visible Light Communication)**

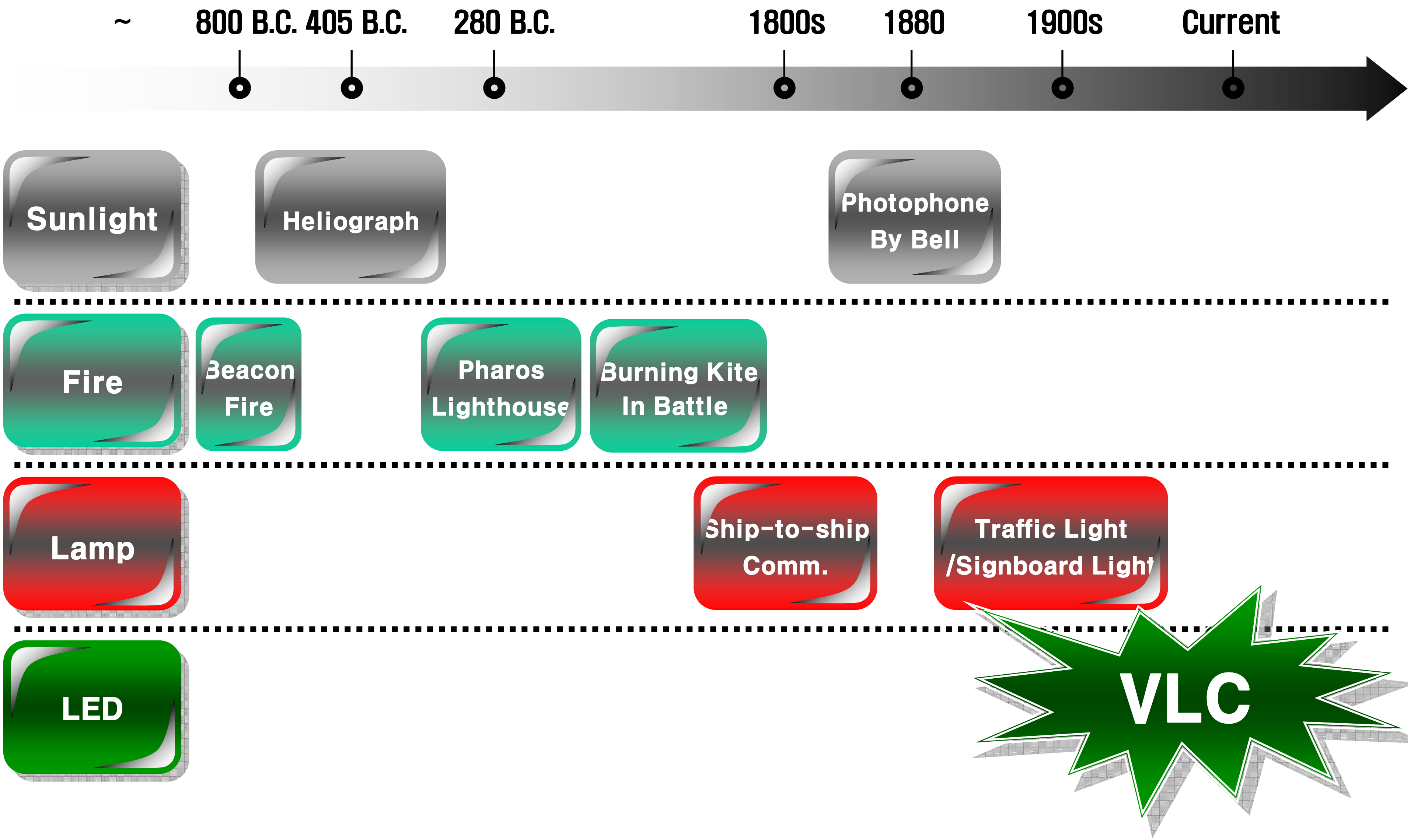
  : **New communication technology using "Visible Light".**

- **Visible Light**

  : **Wavelength between ~400nm (750THz) and ~700nm (428THz)**

- **General Characteristic**
  - Visibility : Aesthetically pleasing
  - Security : What You See Is What You Send.
  - Health : Harmless for human body
  - Unregulated : no regulation in optical frequency
  - Using in the restricted area : aircraft, spaceship, hospital
  - Eye safety

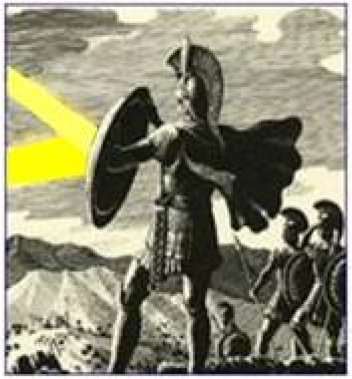
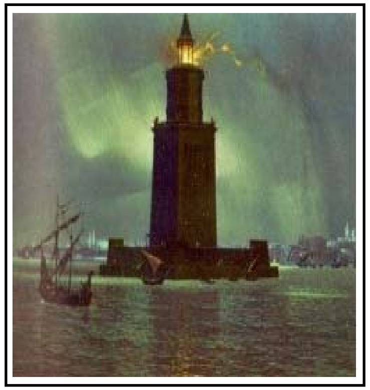
VLC history

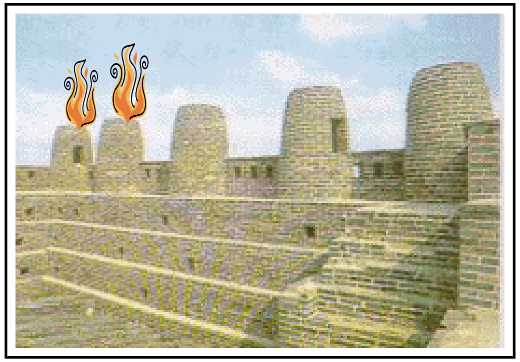
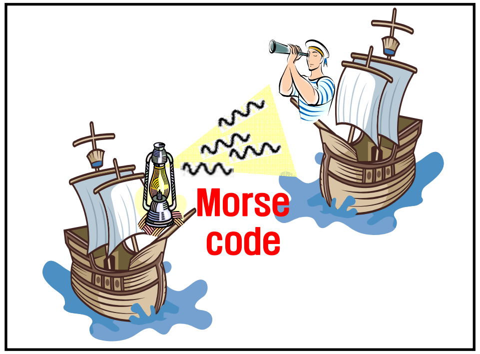


~
800 B.C.
405 B.C.
280 B.C.
1800s
1880
1900s
Current
Sunlight
Heliograph
Photophone
By Bell
Fire
Beacon
Fire
Pharos
Lighthouse
Burning Kite
In Battle
Lamp
Ship-to-ship
Comm.
Traffic Light
/Signboard Light
LED
VLC

VLC history – Low speed

- ❖ Information delivery using mirror reflection (Heliograph)
- ❖ The use of fire or lamp
  - Beacon fire, lighthouse, ship-to-ship comm. by Morse code
- ❖ Traffic light : R/G/B color multiplexing (Walk/Stop)

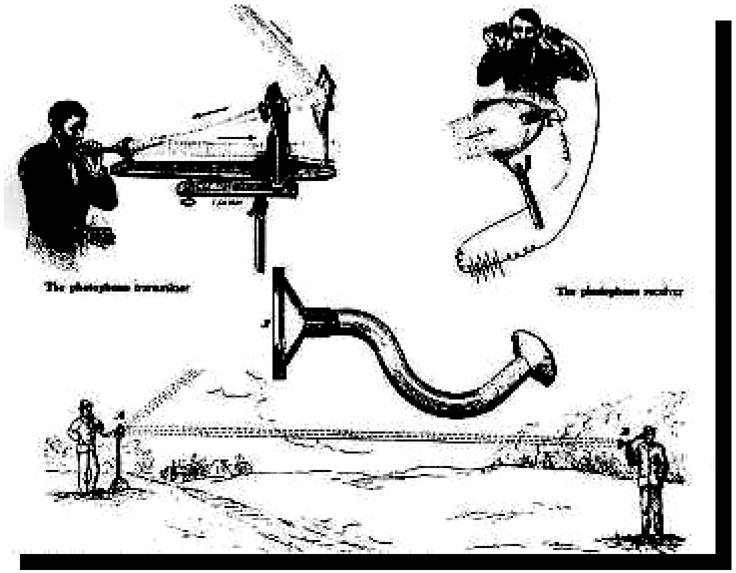



VLC history – Photophone

❖ **Bell's Photophone (1880)**

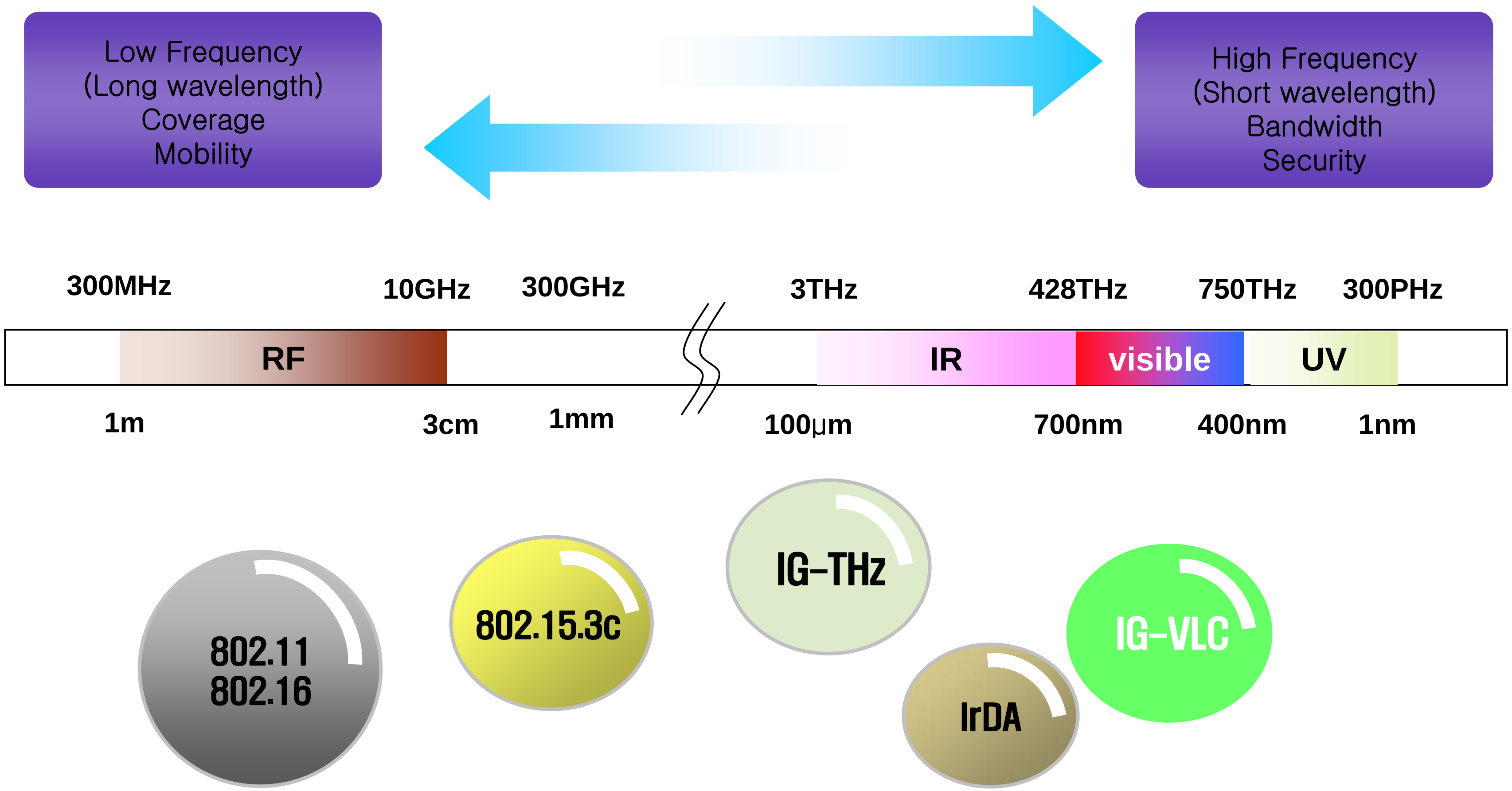
- **Optical source : sunlight**
- **Modulation : vibrating mirror**
- **Receiver : parabolic mirror**
- **Distance : 700 ft (213m)**

http://www.freespaceoptic.com/



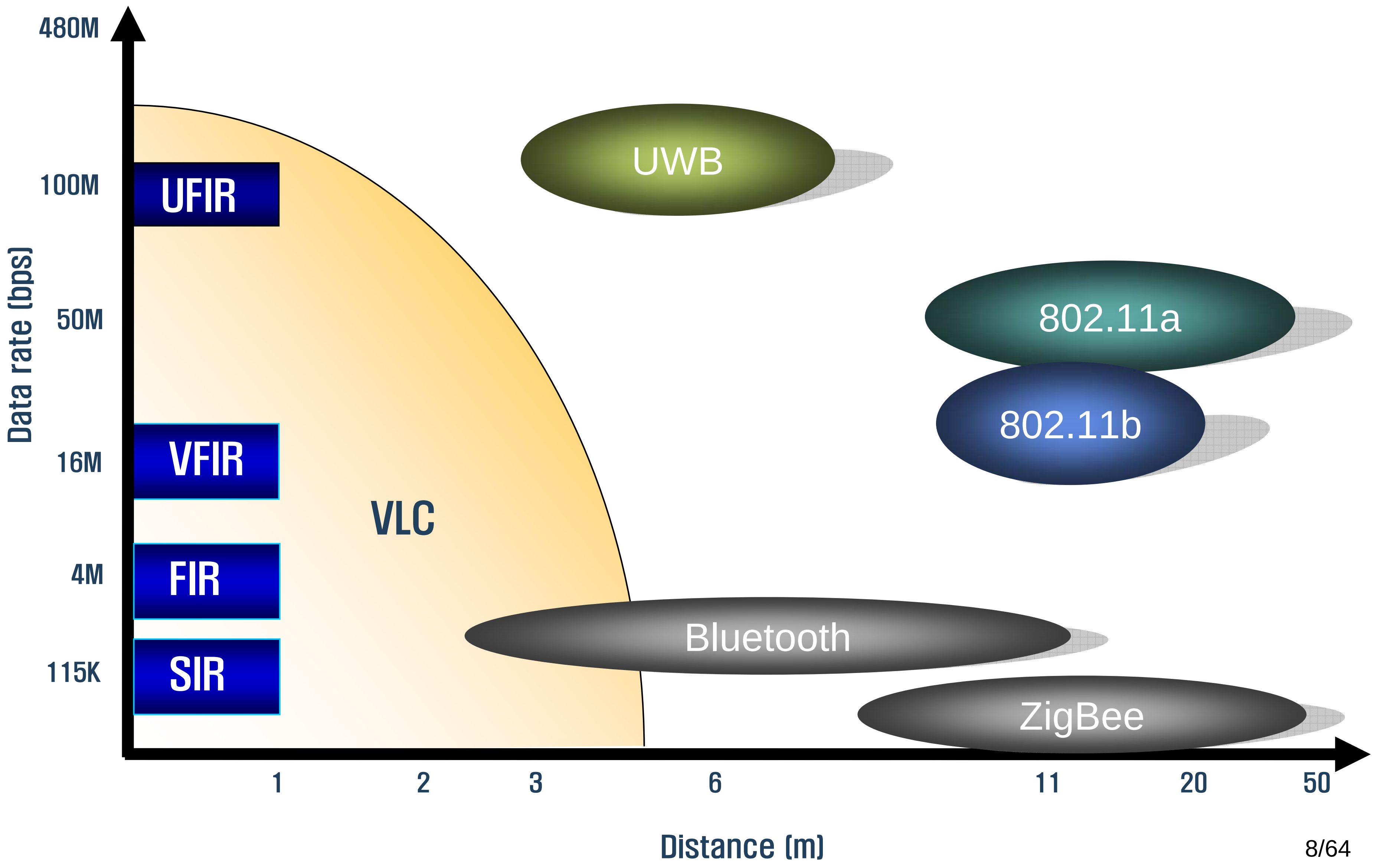
Excerpted from: The New Idea Self-Instructor edited by Ferdinand Ellsworth Cary, A. M. (Monarch Book Company, Chicago & Philadelphia, 1904)

Frequency band for VLC

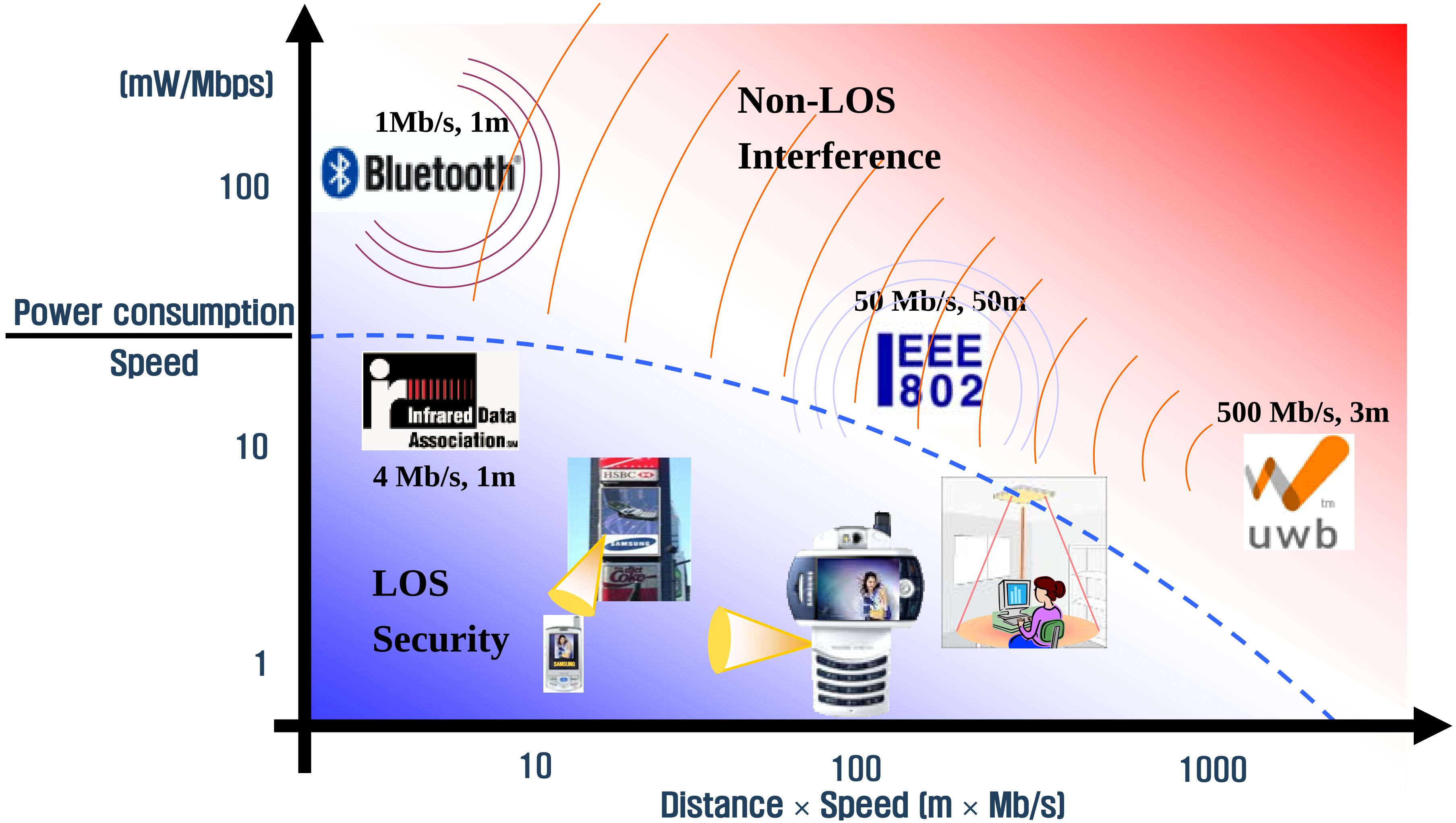


- IG-THz : 300 GHz to 10 THz (contribution 15-07-0623-01)
- 802.15.3c : 57 GHz to 64 GHz
- IrDA : 334THz(900nm) to 353THz (850nm)

VLC Characteristics



VLC Characteristics



Directivity + Simplicity → Optical connectivity saves power

VLC vs. RF Characteristics

Property		VLC	RF
Bandwidth		Unlimited, 400nm~700nm	Regulatory, BW Limited
EMI		No	High
Line of Sight		Yes	No
Standard		Beginning (IG-VLC)	Matured
Hazard		No	Yes
Mobile To Mobile	Visibility (Security)	Yes	No
	Power Consumption	Relative low	Medium
	Distance	Short	Medium
Infra to Mobile	Visibility (Security)	Yes	No
	Infra	LED Illumination	Access Point
	Mobility	Limited	Yes
	Coverage	Narrow	Wide

VLC motivation

- **Communication community trend**
  - Ubiquitous (Connected anywhere, anytime)
  - Security
- **LED trend**
  - LED technical evolution (efficiency, brightness)
  - LED illumination infra
- **Environmental trend**
  - Energy saving
  - No E-smog
- **Intrinsic characteristic of VLC**
  - Visibility
  - No interference / No regulation

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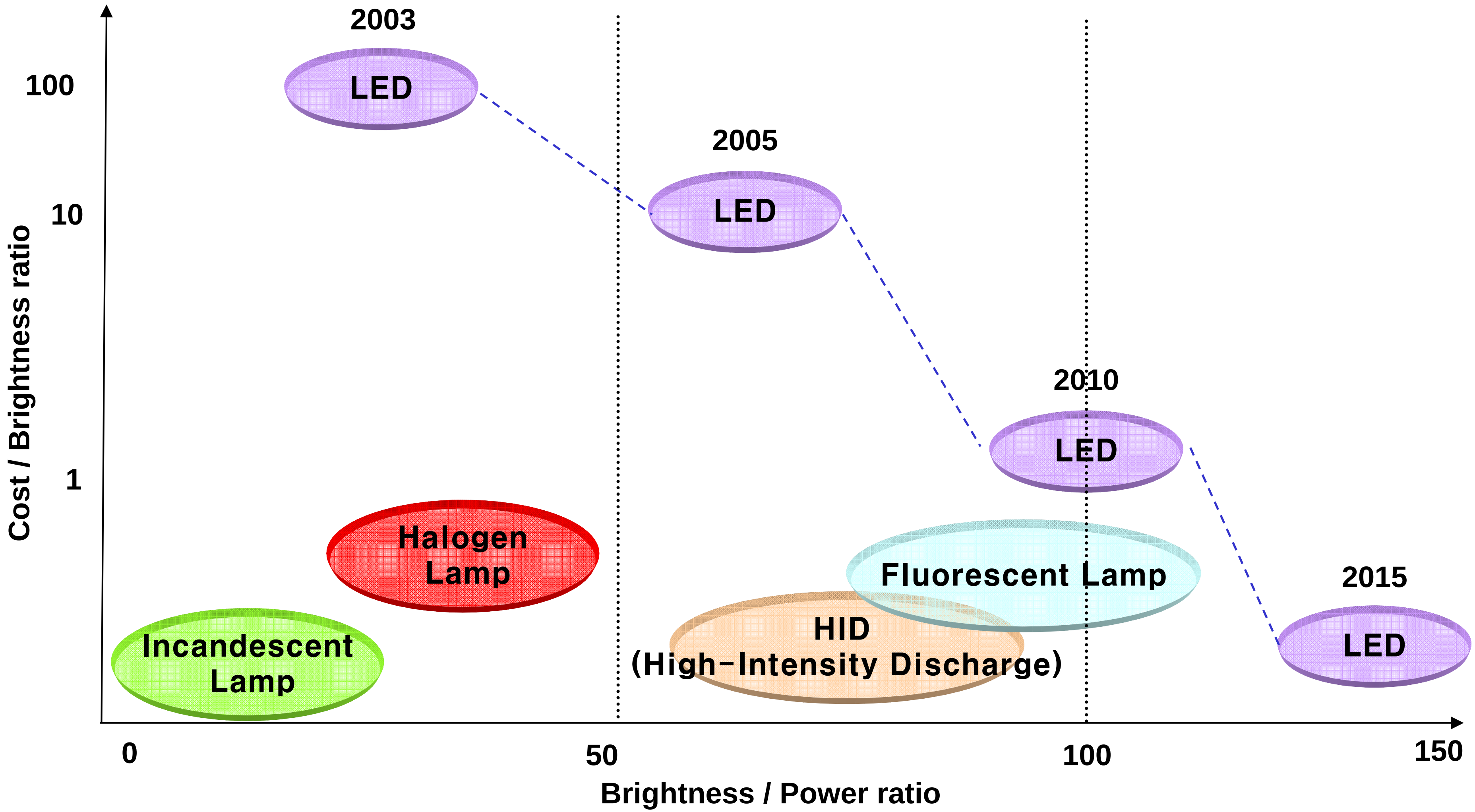
LED technical evolution

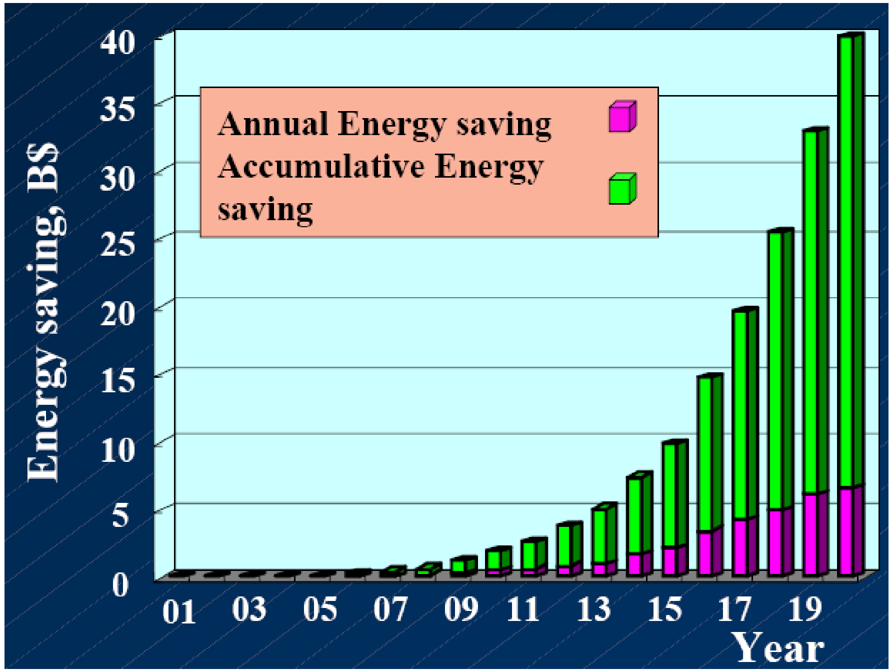
❖ Performance and Price comparison



Source: Credit Suisse, 2006.11.2

LED driver (environmental perspective)

- Environment protection
  - Kyoto Protocol : CO_2 emission regulation
  - RoHS : Hg-free bulb
  - WEEE : Producer responsibility
- Energy saving
  - Electricity in Korea
    - 278 TWh(2002), 7.2 % of USA
  - 20% for Lighting : 55.6 TWh
  - 50% saving by LED : 27.8TWh
  - Energy Saving Effect:
    - 3 Nuclear Stations (1GW/day)
    - 2 B$/year

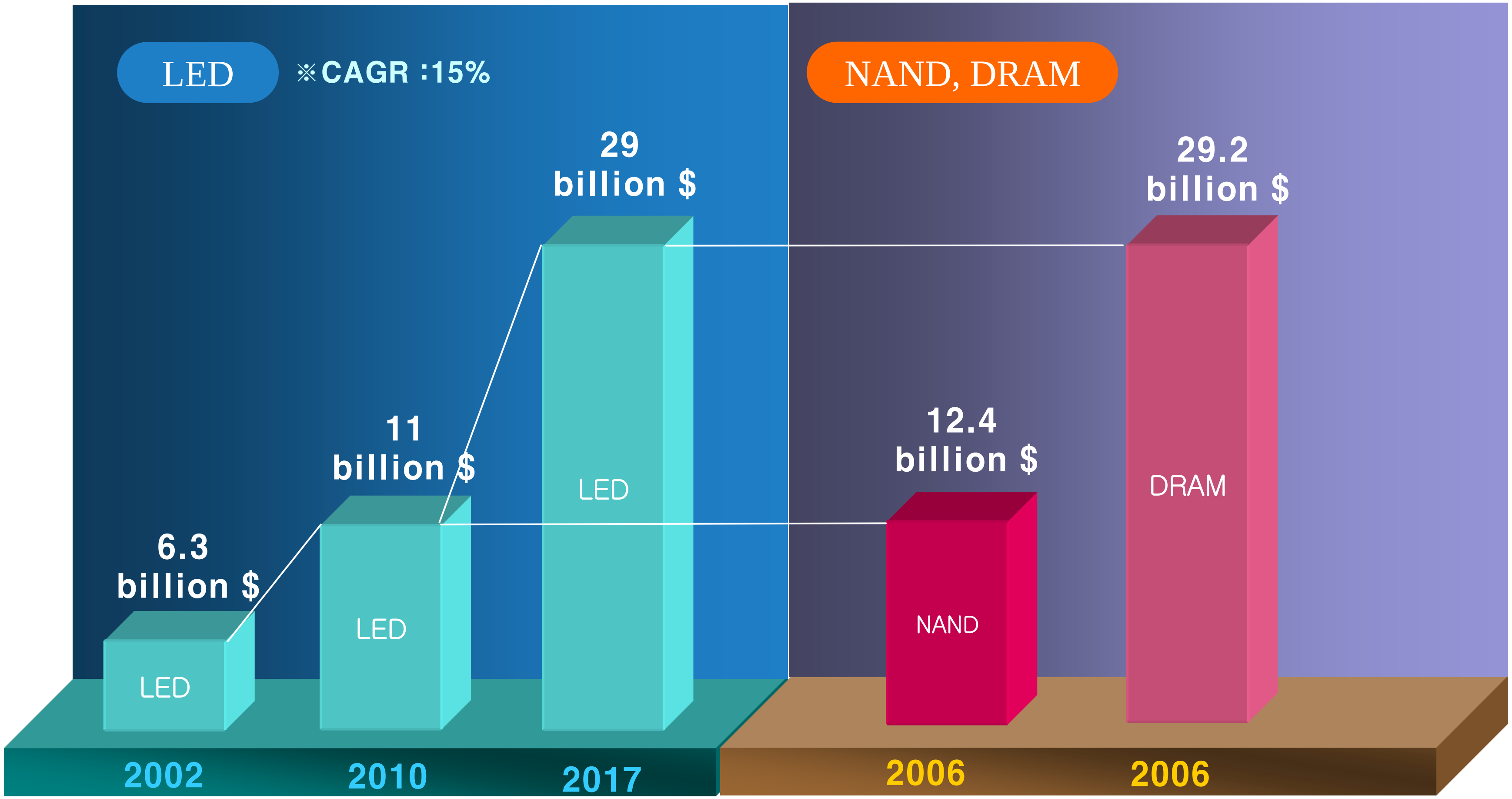


Source: KOPTI (The Korea Photonics Technology Institute)

RoHS : Restriction of the use of Certain Hazardous Substance
WEEE : Waste Electrical and Electronic Equipment

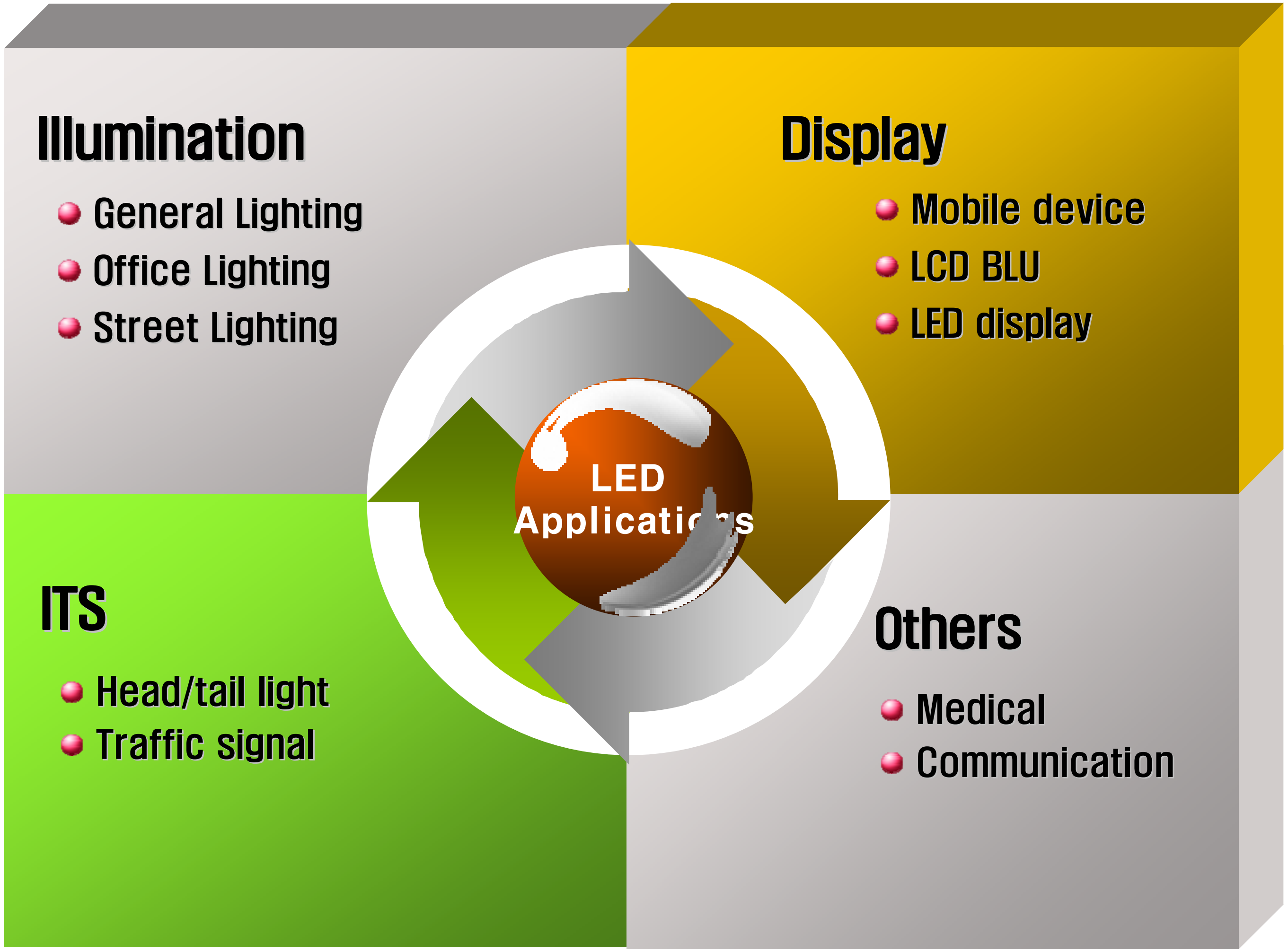
LED Market Forecast

❖ LED market comparison with NAND, DRAM

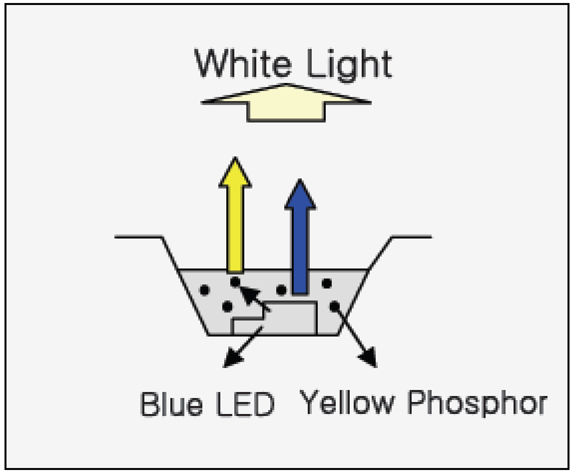


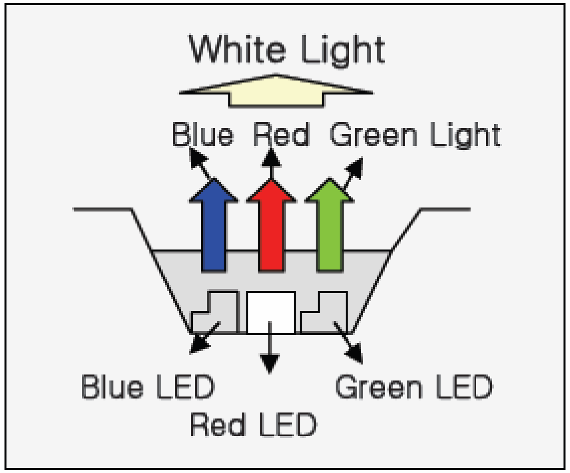
Source: Deutsche Bank, 2007. 2

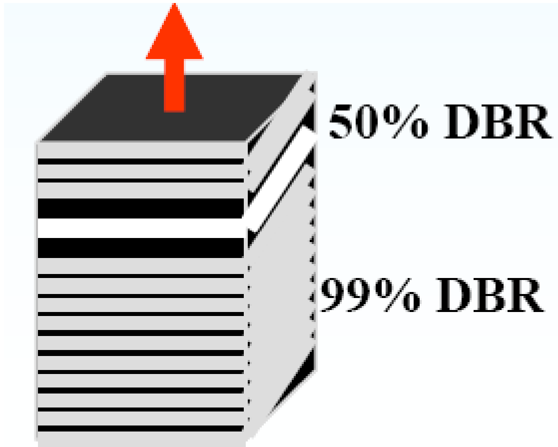
LED application



LED modulation characteristics







B + Phosphor LED	R+G+B LED	RCLED
~40 Mbps	~100 Mbps	~500 Mbps

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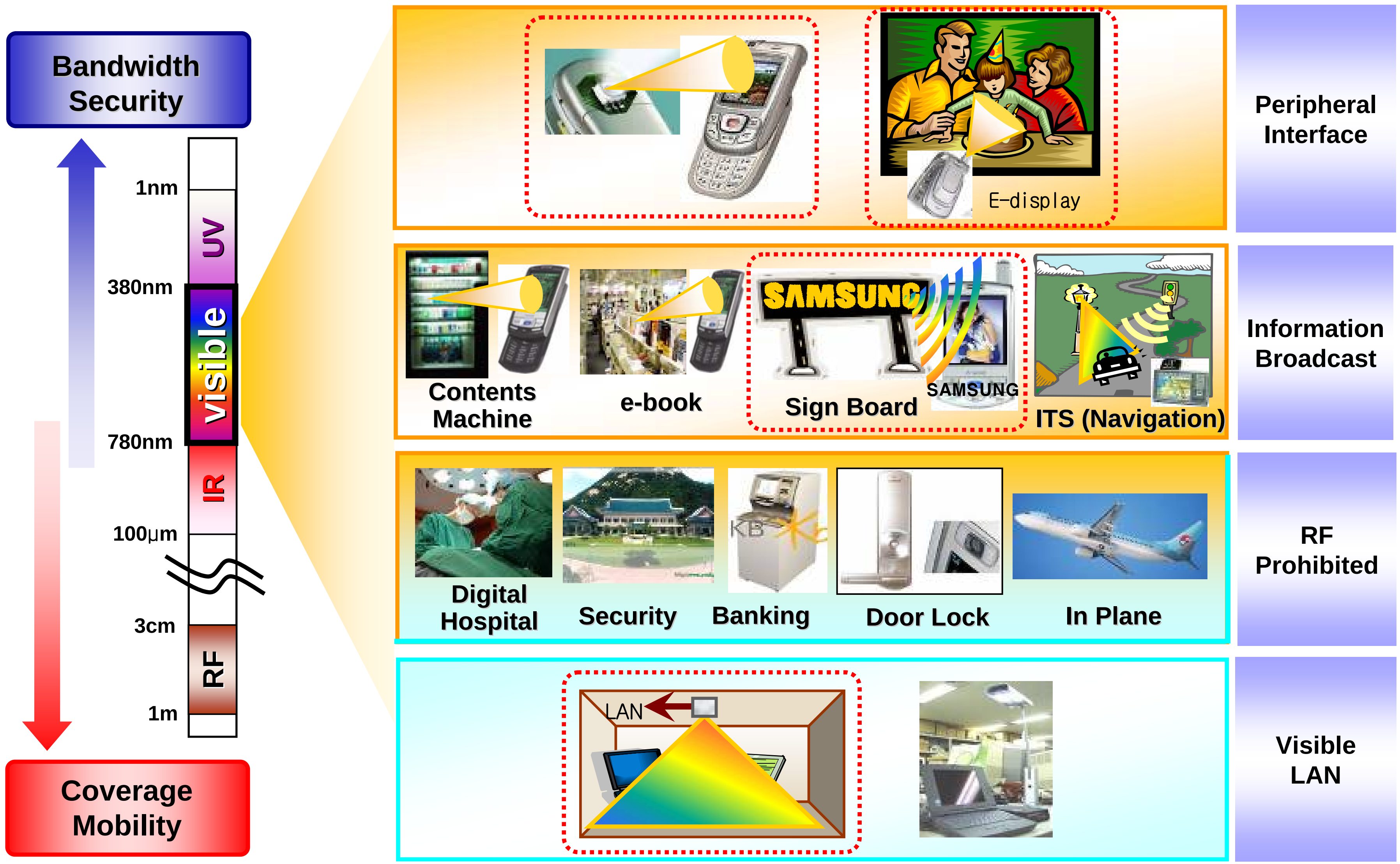
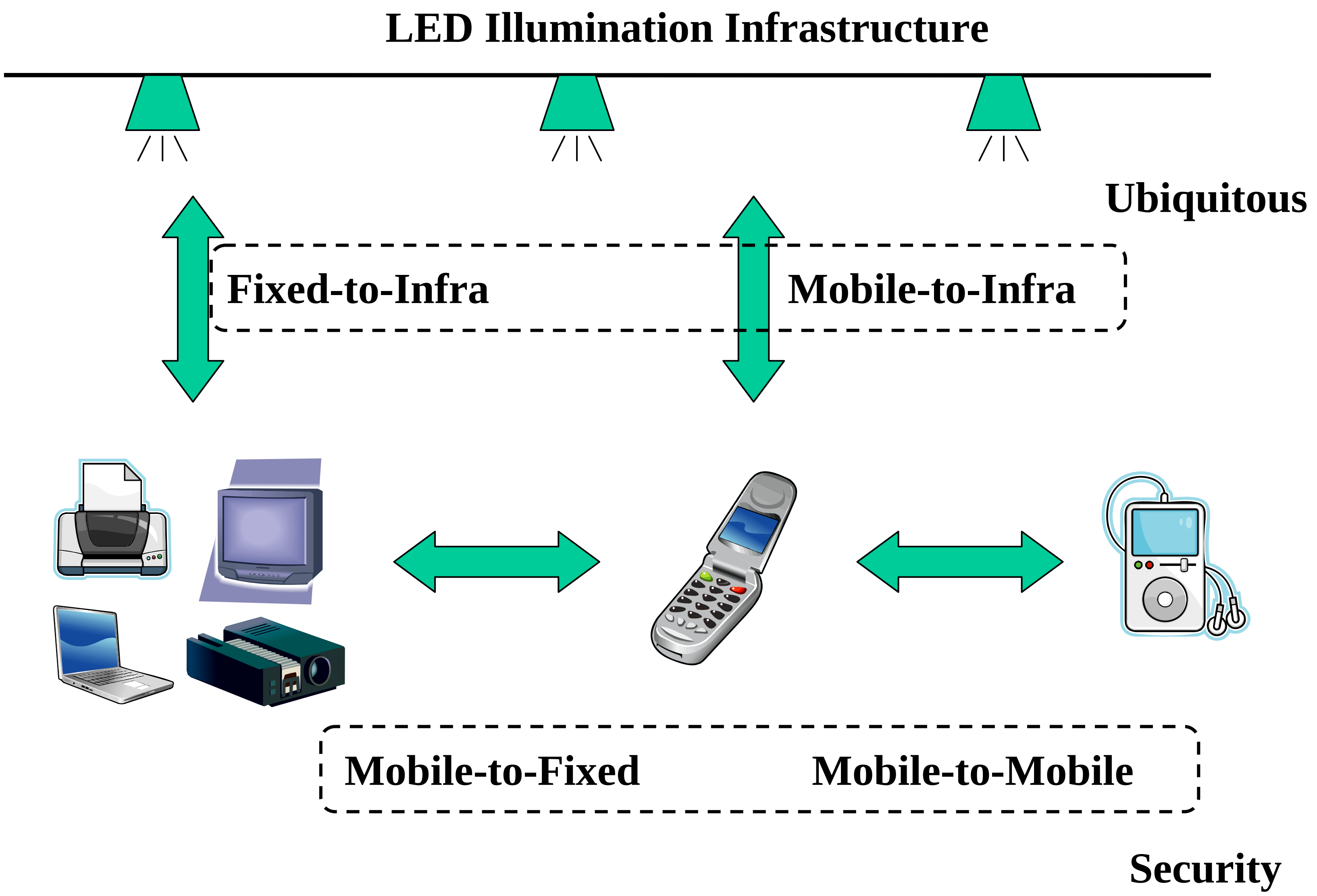
VLC application



Indoor application

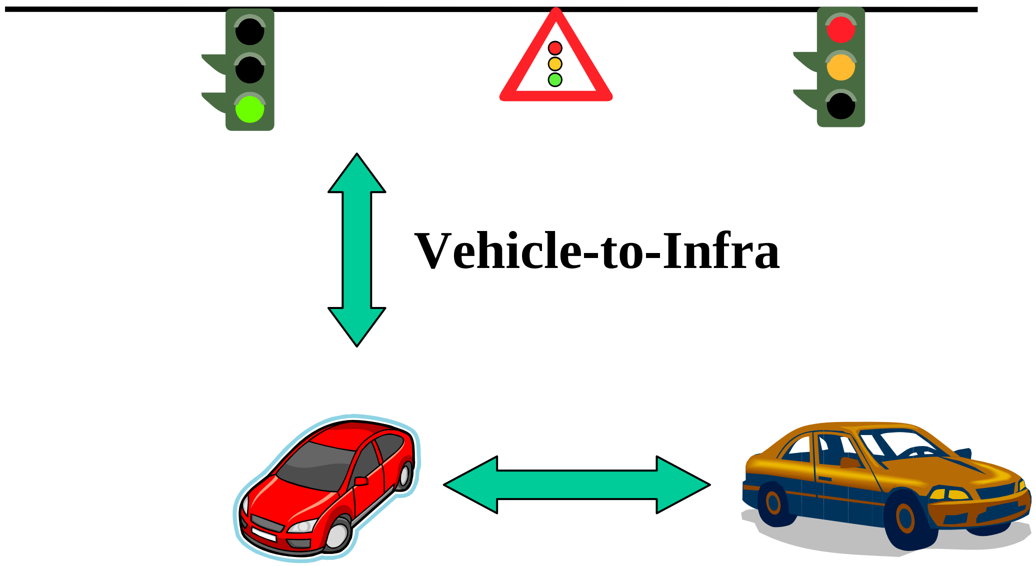


Requirements (Indoor application)

	Mobile to Mobile	Mobile to Fixed	Mobile to Infra	Fixed to Infra
Link	Bi-direction	Bi-direction	Bi or Uni	Bi or Uni
Reach	~1m	~1m	~3m	~3m
Rate	~100Mbps	~100Mbps	~10Mbps	~10Mbps
Application	Contents sharing	File transfer Video streaming M-commerce	Indoor navigation LBS Networked robot	Data broadcast
Alternative	IrDA, Bluetooth, UWB	IrDA, Bluetooth, UWB		WLAN

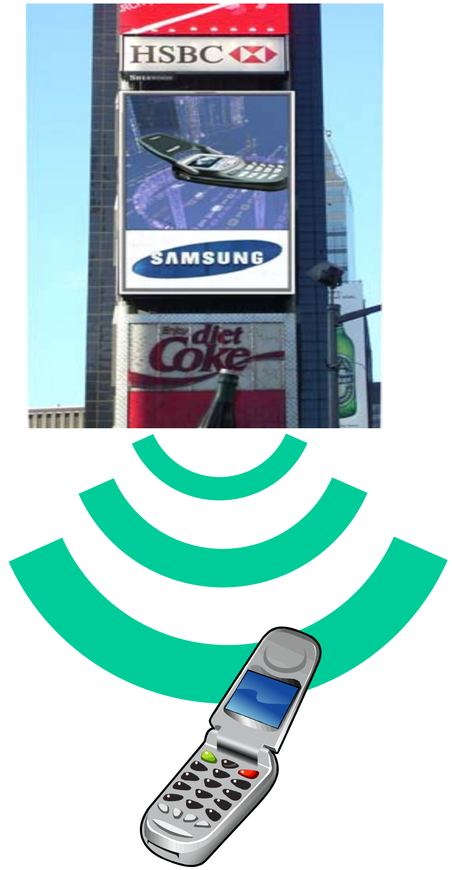
Outdoor application

Traffic control Infrastructure

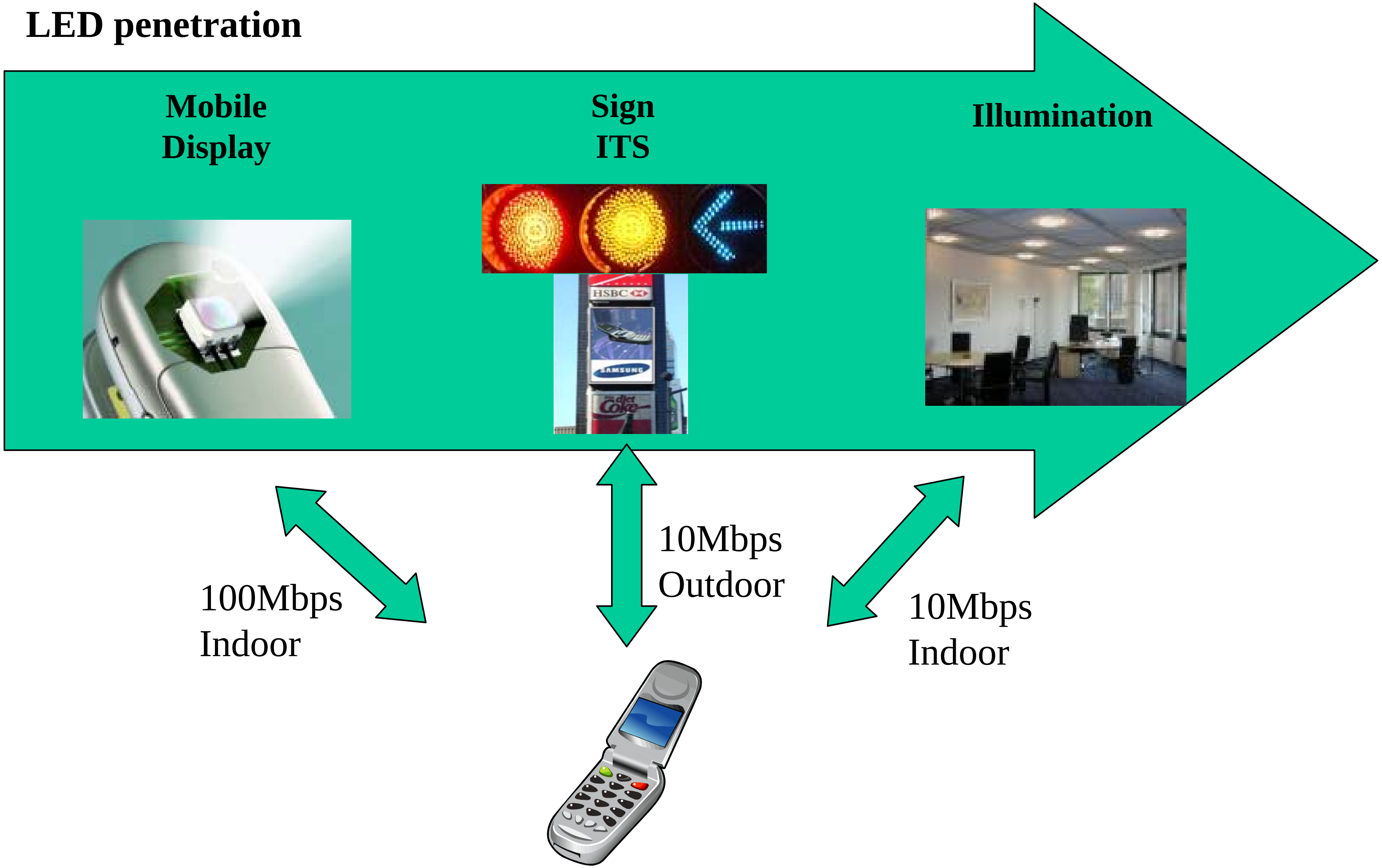


Vehicle-to-Vehicle

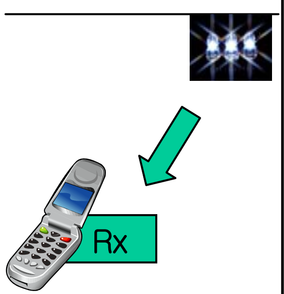
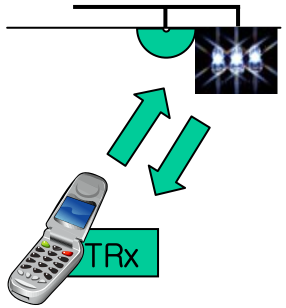
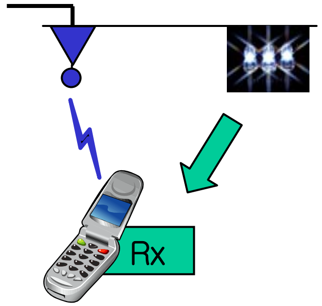
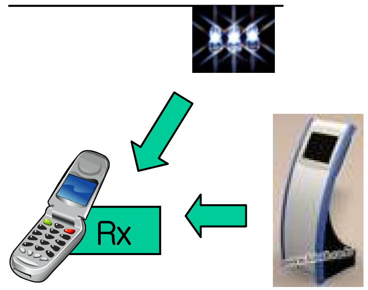
Outdoor advertising



VLC application evolution

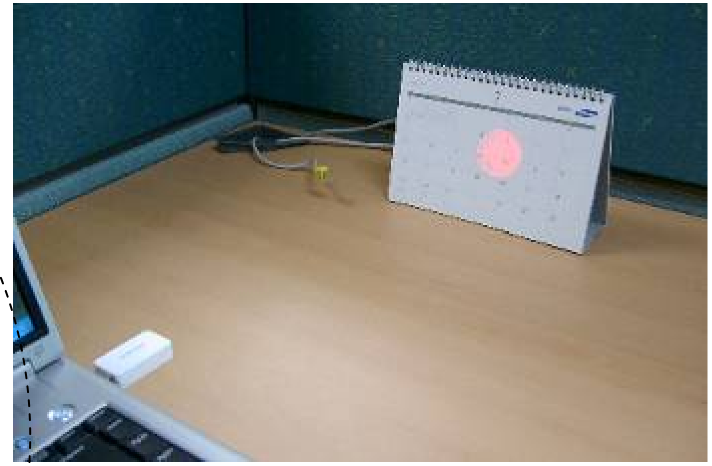


Indoor navigation scheme

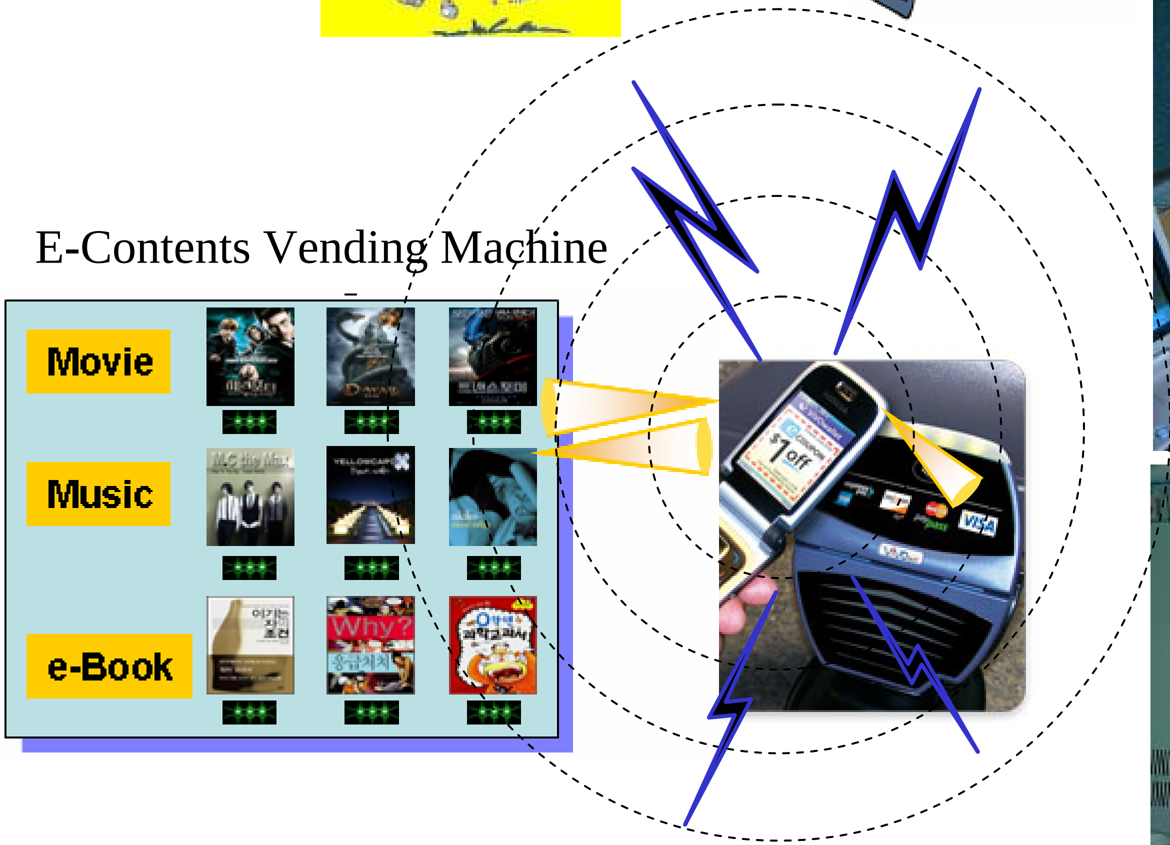
	Uni-direction	Bi-direction	Hybrid	Hot spot
Link				
Rate	▪ Down : ~10kbps	▪ Down : ~10Mbps ▪ Up : ~100Mbps	▪ Down : ~10kbps ▪ Up : ~10Mbps	▪ Down(light) : ~10kbps ▪ Down(HS) : ~100Mbps
Infra	▪ Lighting with optical ID	▪ Lighting with optical ID ▪ Receiver ▪ In-building network ▪ Routing server	▪ Lighting with optical ID ▪ RF access point ▪ In-building network ▪ Routing server	▪ Lighting with optical ID ▪ Hot spot
Mobile	▪ Receiver ▪ Large storage ▪ Map info ▪ Routing software	▪ Receiver ▪ Transmitter	▪ Receiver ▪ RF connectivity	▪ Receiver ▪ Large storage ▪ Routing software
Other service		LBS Ad-hoc connection	LBS	

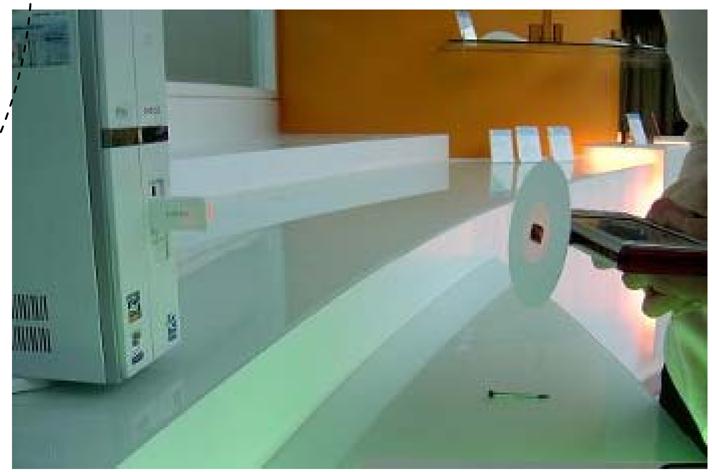
High-speed high-security connectivity

What You See Is What You Send (WYSIWYS)



E-Contents Vending Machine

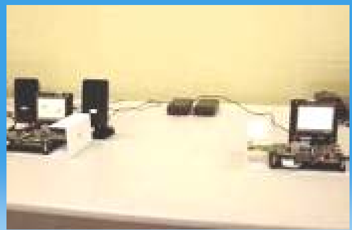




Demonstrations

High speed

Mobile to Mobile
(100Mbps,Samsung)

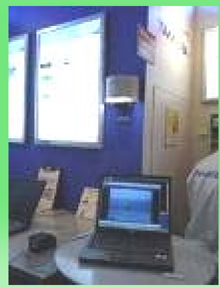


Tx, Rx
(~30Mbps,Oxford Univ.)

LED array
(~1Gbps, Keio Univ.)

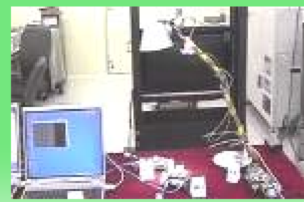
Music broadcasting
(6Mbps, Oxford Univ.)

Infra to Mobile
(10Mbps, Tamura Inc.)



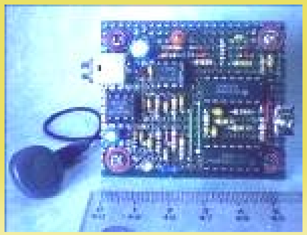
Sign board
(10Mbps, Samsung)

Infra to Mobile (LAN)
(4Mbps, Samsung)



Low speed

Audio transmission
(100kbps, Hongkong Univ.)

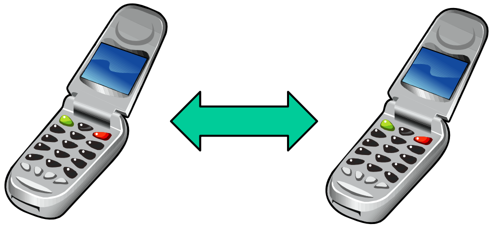


Infra to Mobile, VLCC (Keio Univ., NEC, Toshiba, Sony, Matsushita, Casio etc.)
(4.8kbps, illuminations, visible light ID, sign board, applications based on JEITA)

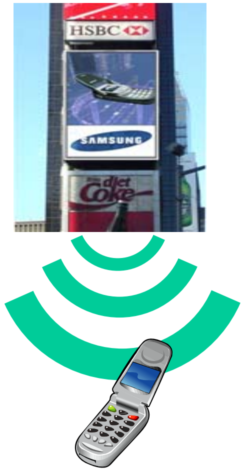



VLC Demonstrations

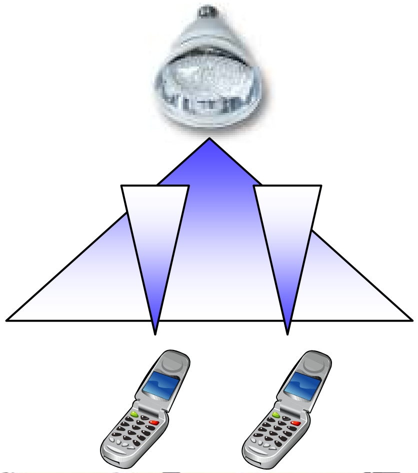
Mobile to mobile

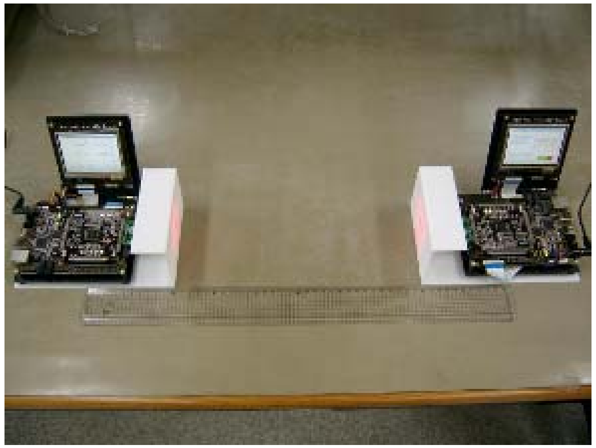


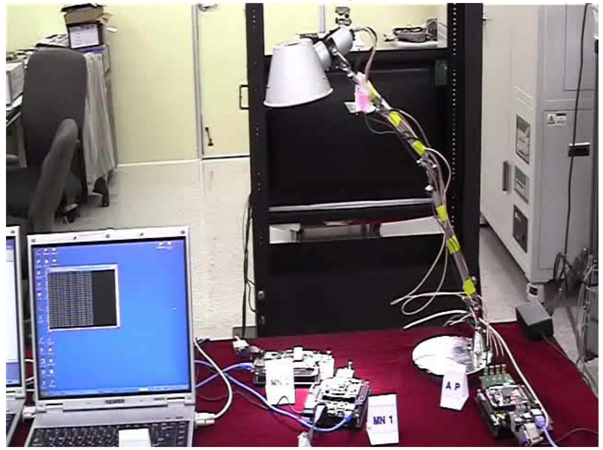
Infra to mobile



Infra to mobile







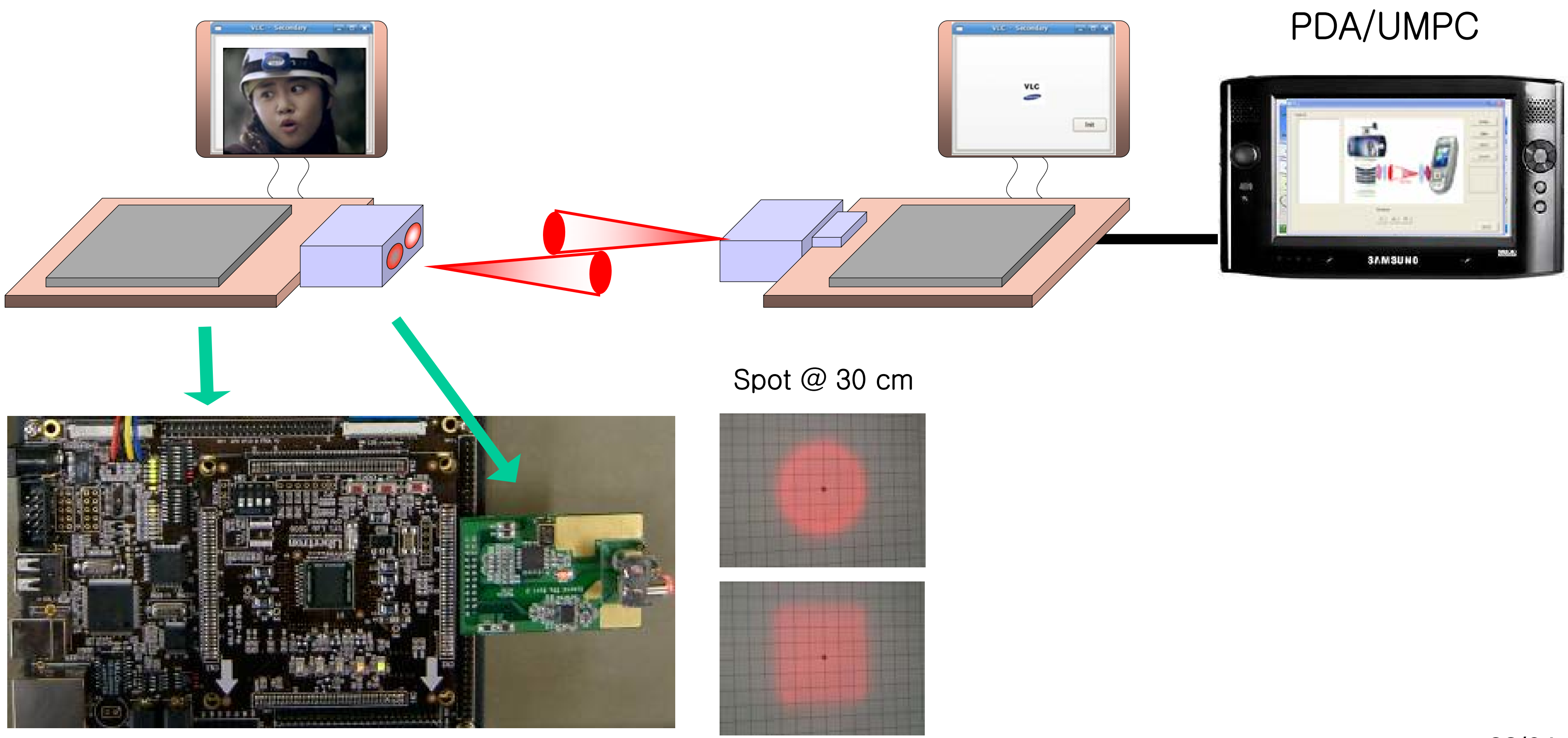
100 Mbps, 1m
Bidirection

20 Mbps, 3m
Unidirection

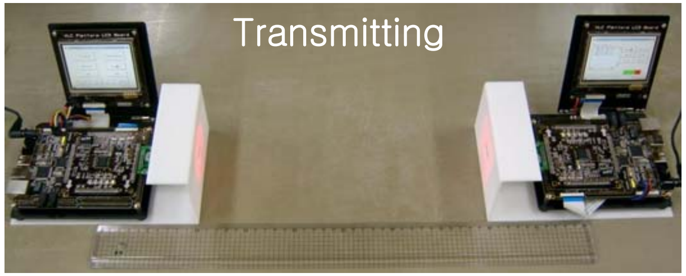
4 Mbps, 3m
Bidirection

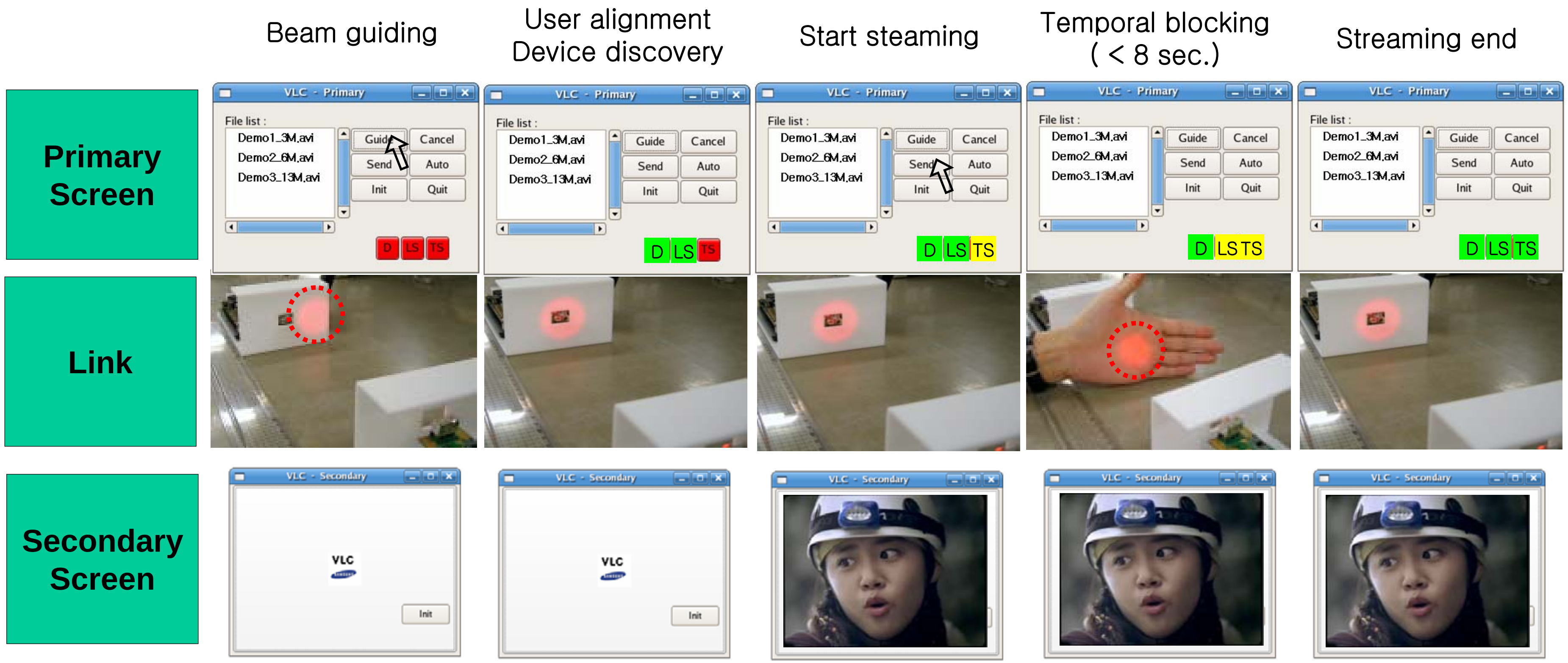
Mobile-to-mobile demo

- What You See Is What You Send (WYSIWYS)
- 120 Mbps, 1m, Full duplex
- File transfer and video streaming

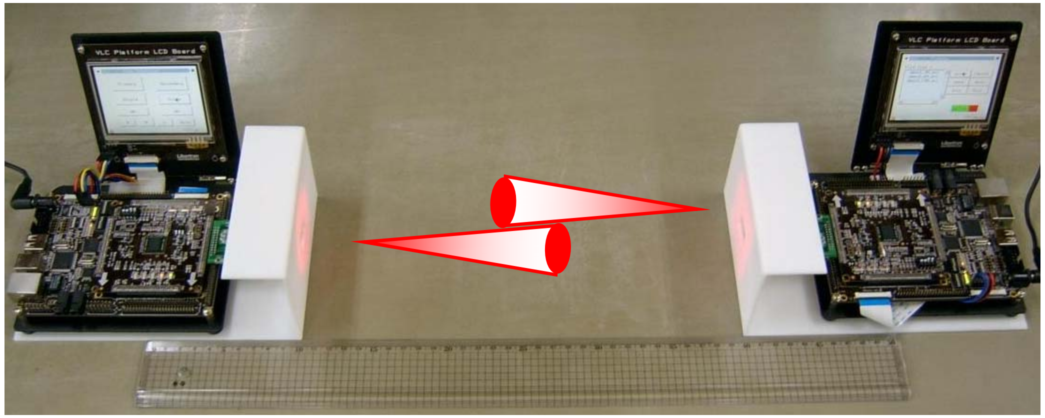


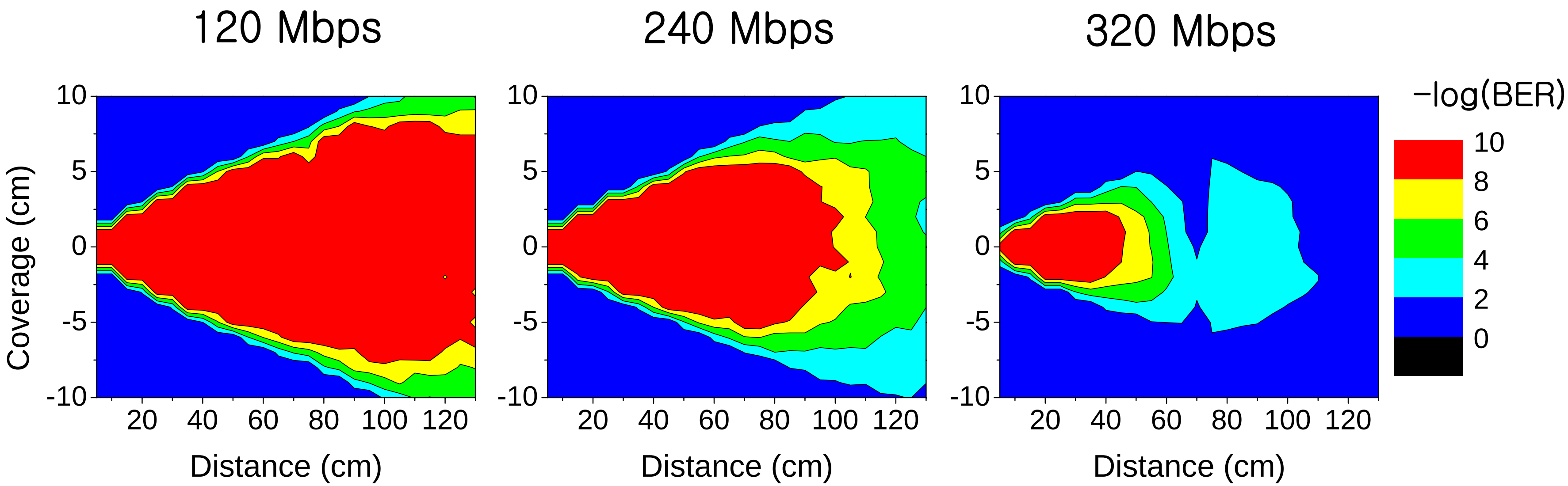
Mobile-to-mobile (protocol)





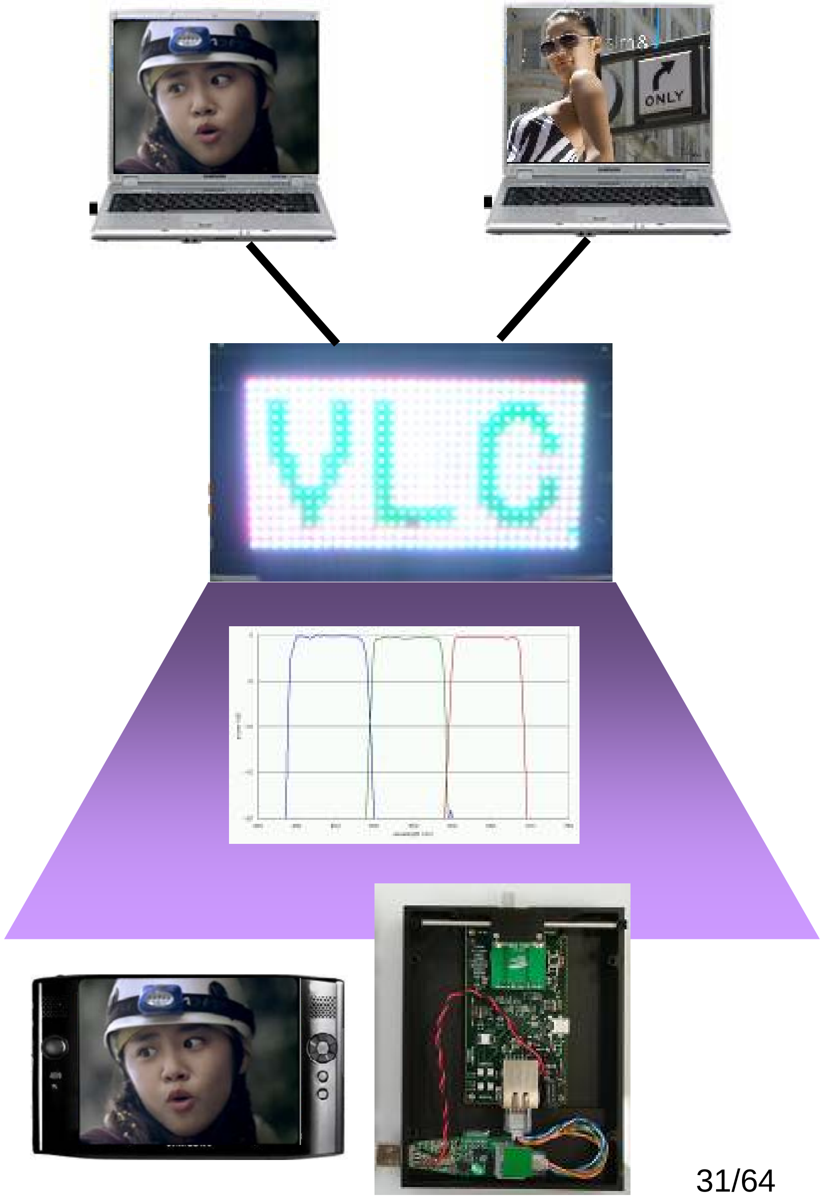
Mobile-to-mobile (Link performance)





Infra-to-mobile demo

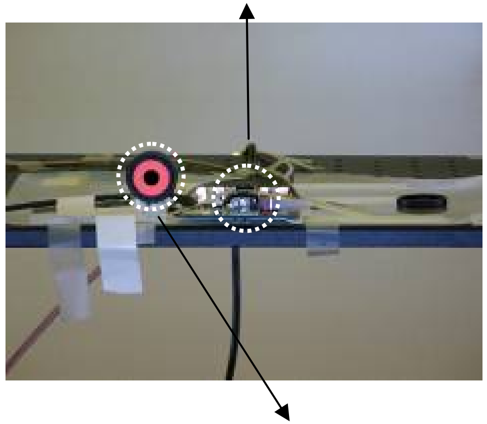
- RGB WDM transmission
- 20 Mbps, 3m, Uni-direction
- Information broadcast from sign board



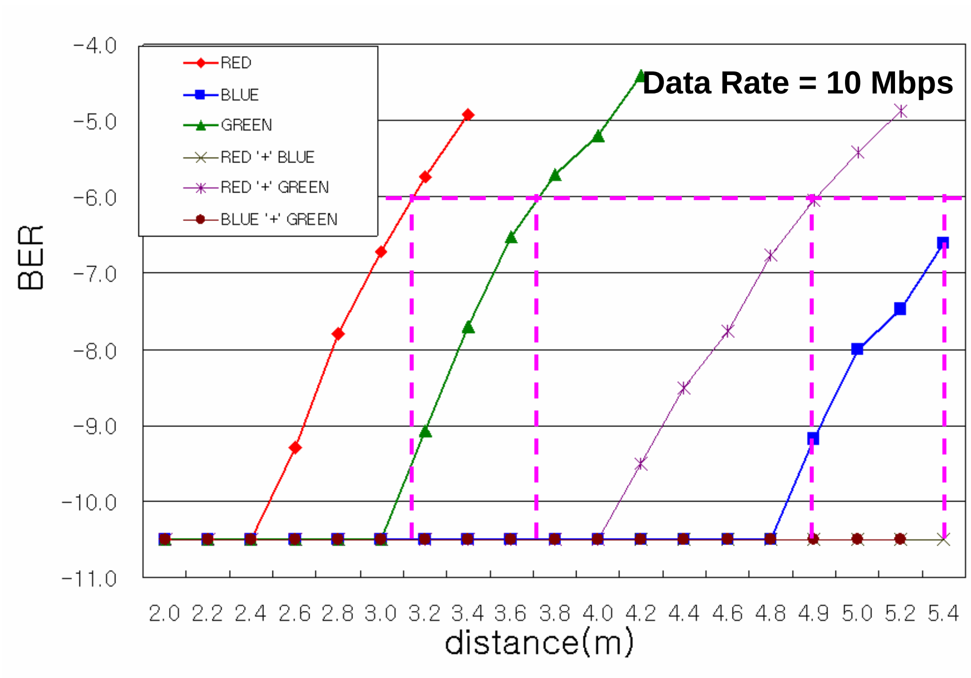
Infra-to-mobile (Link performance)

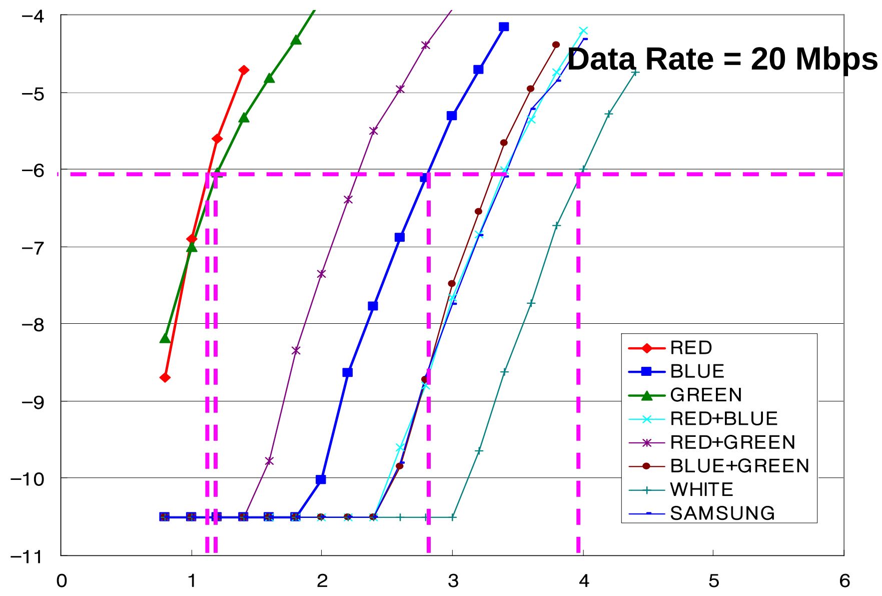
Transmitter (RGB Sign-Board)

Receiver (Silicon PD)



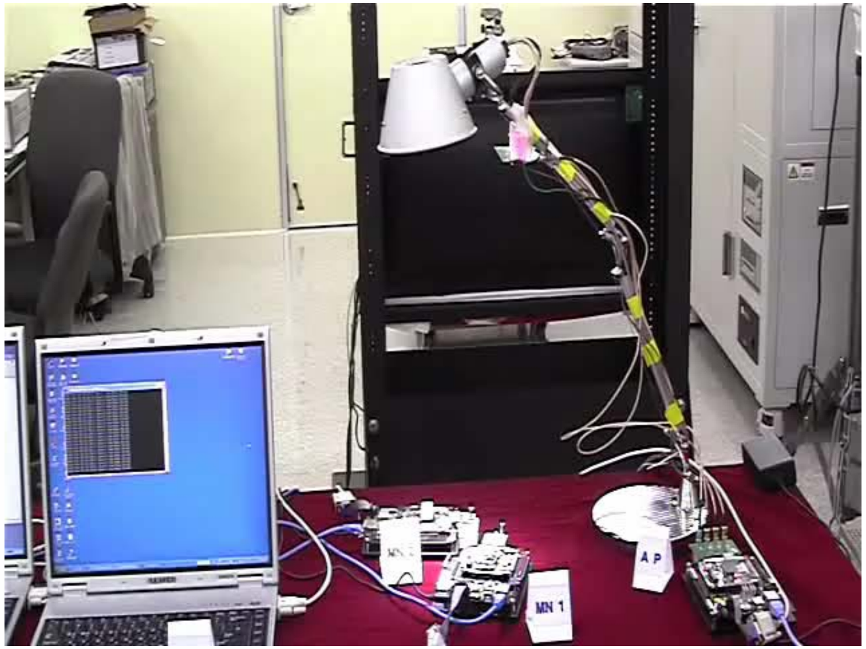
Power Meter

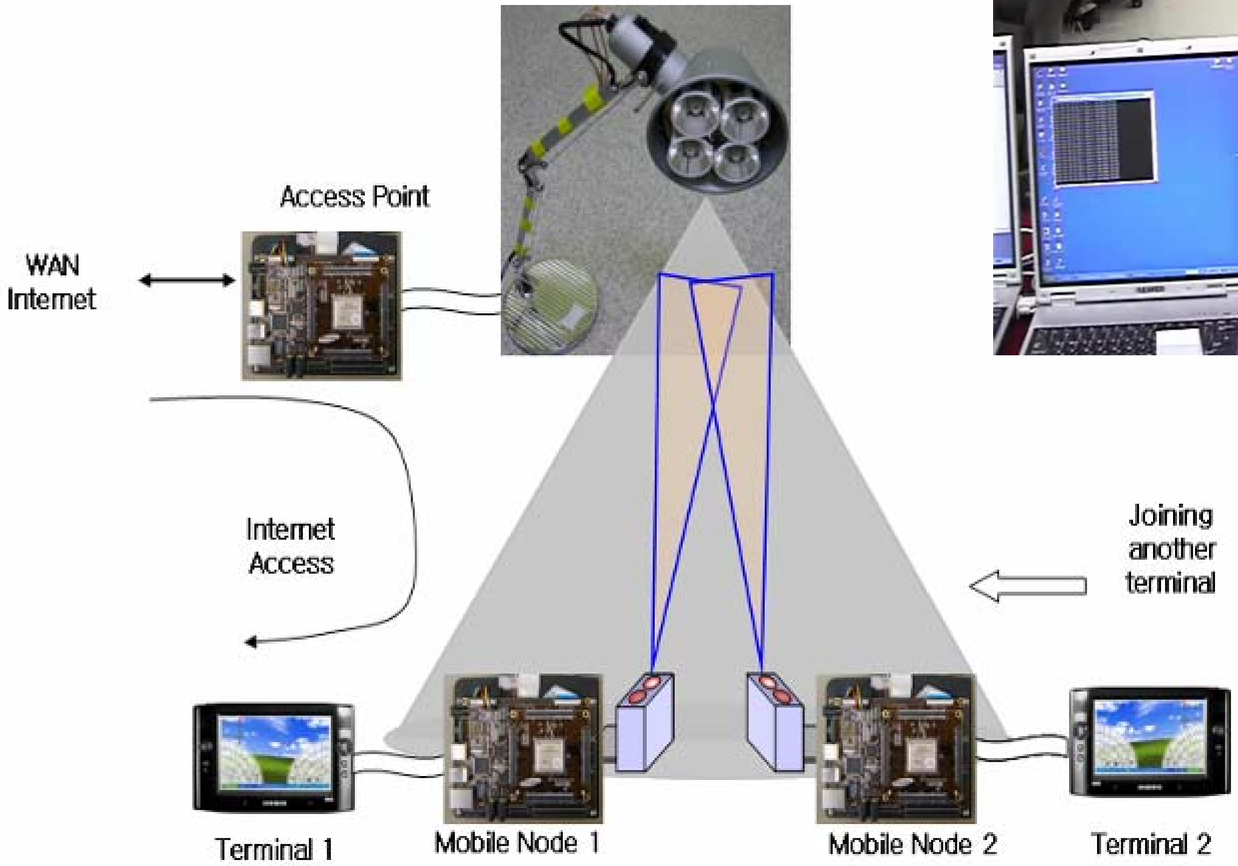




Infra-to-mobile

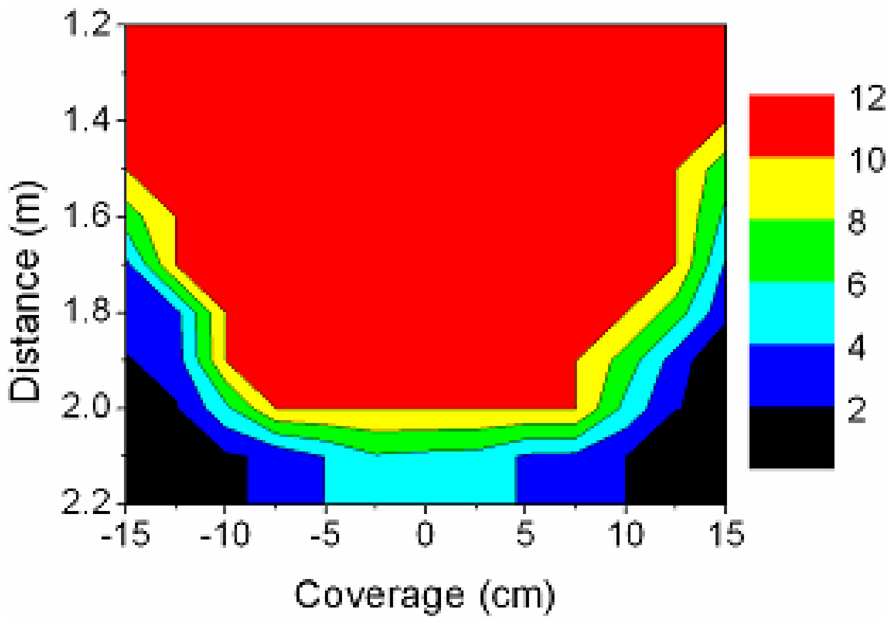
- TDMA-based P2MP
- 4 Mbps, 3 m, bi-direction
- Secure indoor LAN



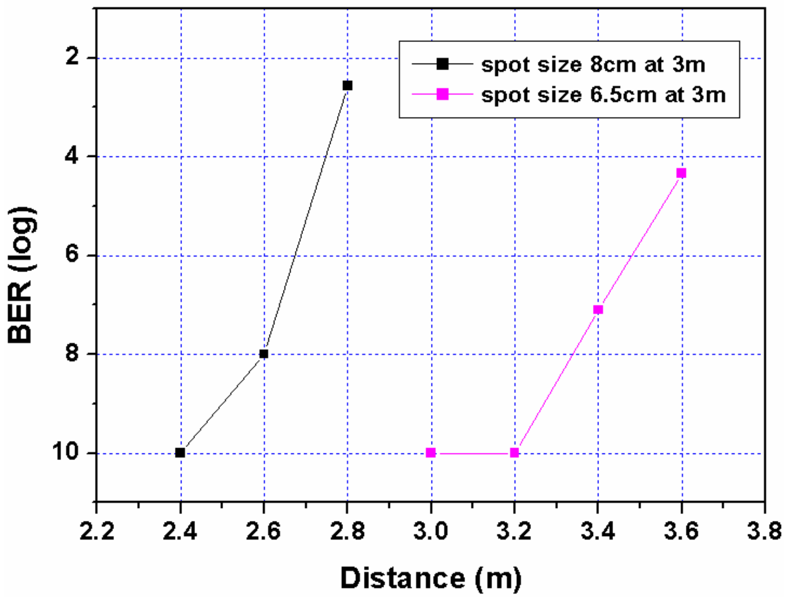


Infra-to-mobile (Link performance)

- Downstream : White LED



- Upstream : LD



Summary (Part 1)

- VLC introduction
  - VLC history
  - Motivation
- LED introduction
  - LED technical evolution
  - LED market forecast
  - LED application
  - LED modulation characteristics
- VLC potential application
  - Application category
  - Indoor : Navigation, High-speed connectivity
  - Outdoor : ITS, Advertising
  - Demonstration
    - Demonstration overview
    - Mobile-to-mobile
    - Infra-to-mobile

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Visible Light Communications

Dominic O'Brien, University of Oxford,

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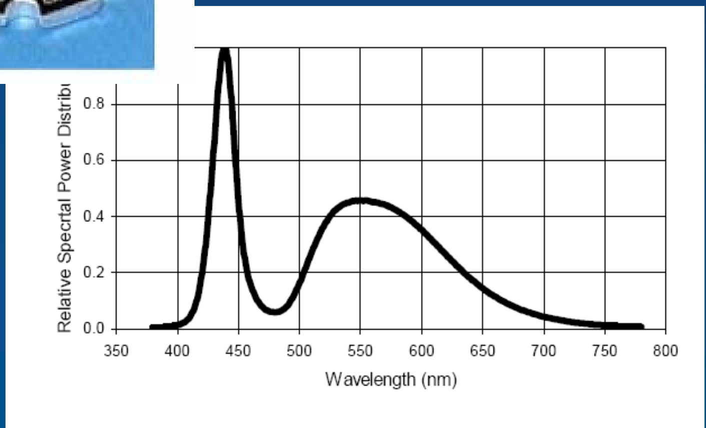
Contributions from Communications Group at Oxford

Overview

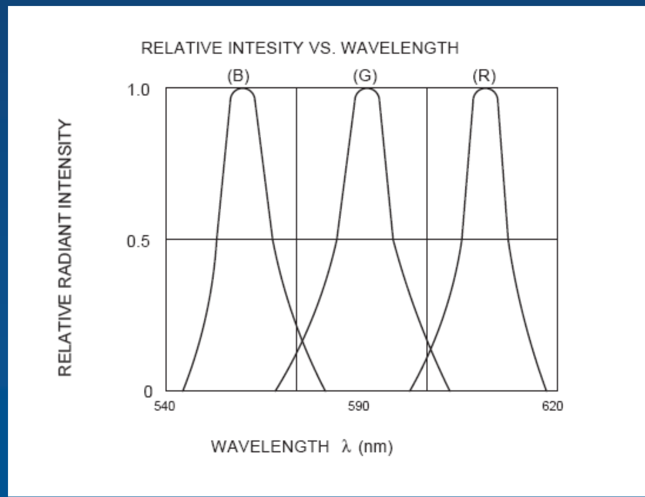
- Visible Light Communications
  - Transmitter
  - Channel
  - Receiver
- Technical challenges
  - Higher bandwidth
  - Enabling mobility and reliability
- Conclusions

VLC Sources

- Blue LED & Phosphor
  - Low cost
  - Phosphor limits bandwidth
  - Modulation can cause colour shift
- RGB triplet
  - Higher cost
  - Potentially higher bandwidth
  - Potential for WDM
  - Modulation without colour shift



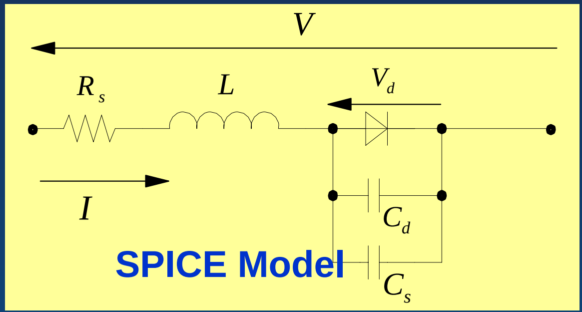
Single chip LED spectrum



RGB LED spectrum

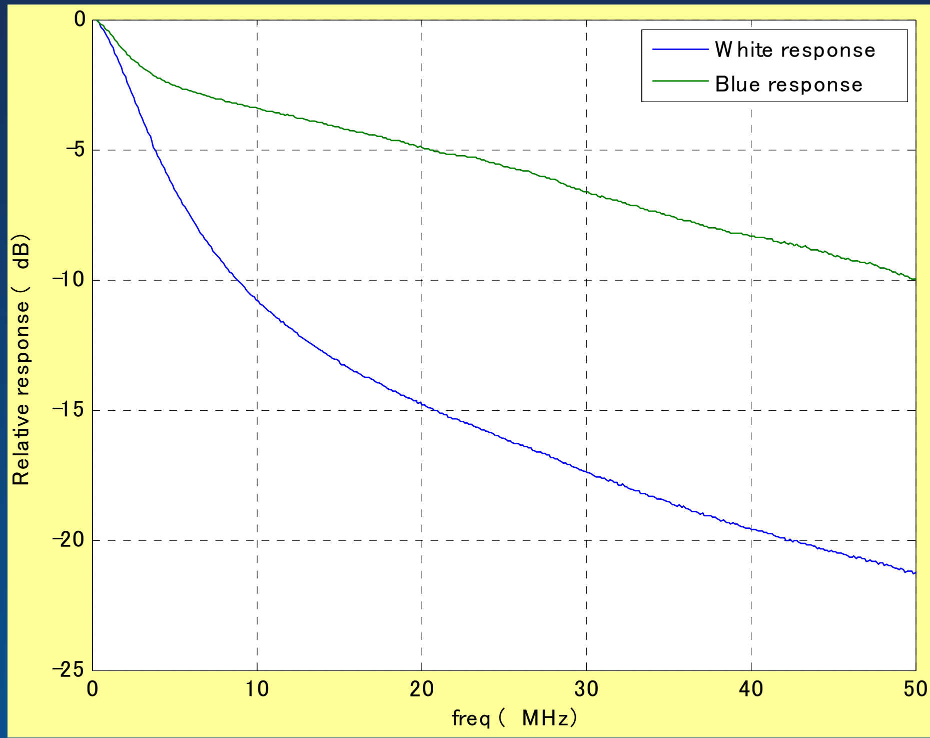
LED Modulation

> **Opto-electronic response**



Luxeon LED

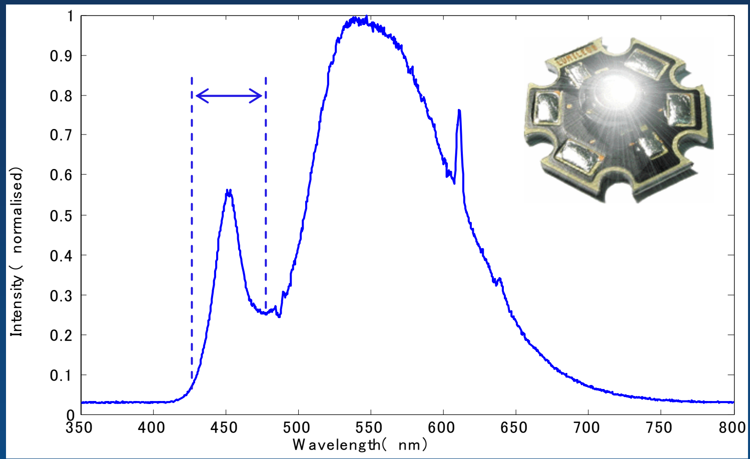
***R_s* = 0.9727 Ω**
***L* = 33.342 nH**
***C_s* = 2.8 nF**
***C_d* = 2.567 nF**
***tt* = 1.09 ns**



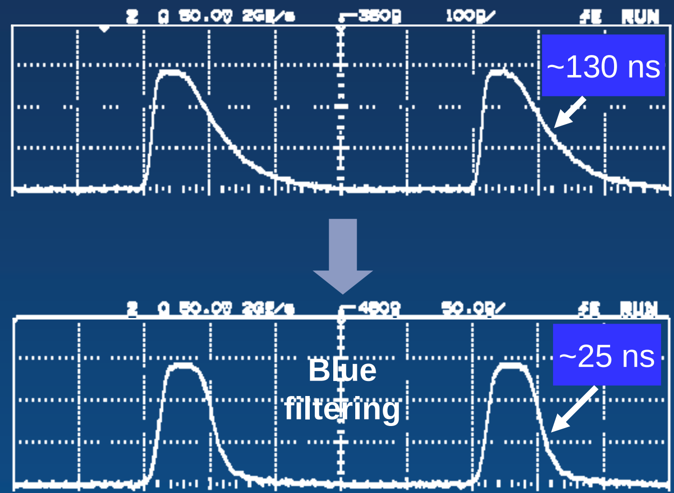
Measured LED small-signal bandwidth

Improvement of LED response

- Using blue-response only (blue filtering)



Measured optical spectrum



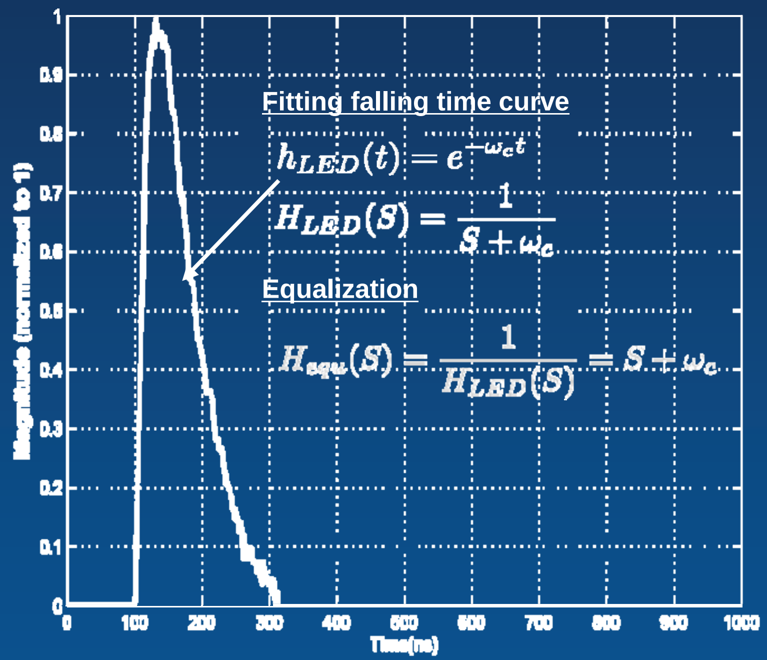
Measured impulse response

- **Issue: Only 10% of signal power is recovered**
  ⇒ Reducing SNR, link distance
- **LEDs with more blue energy [1] could be used to gain more filtered power, however the balance of white colour is shifted**

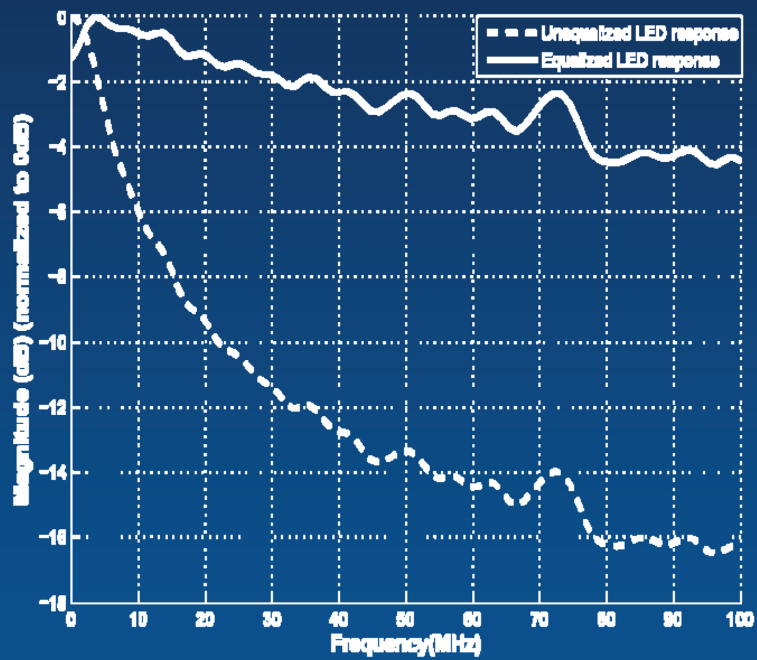
[1] Grubor, J., et al., "Wireless high-speed data transmission with phosphorescent white-light LEDs", Proc. ECOC 07 (PDS 3.6), pp. 1-2. ECO [06.11], 16-20 Sep. 2007, Berlin, Germany

Improvement of channel response

> **Receiver equalisation**



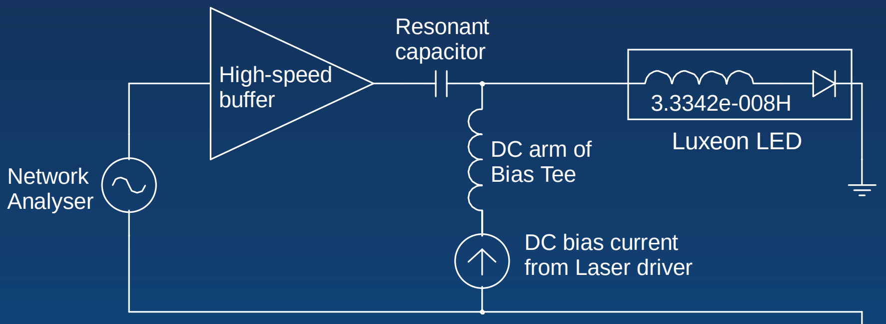
Measured LED impulse response



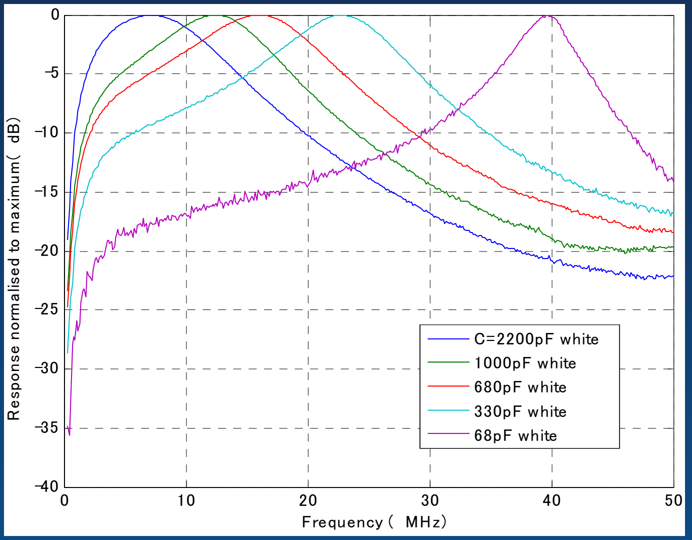
Improved LED transmission BW

Improvement of LED bandwidth

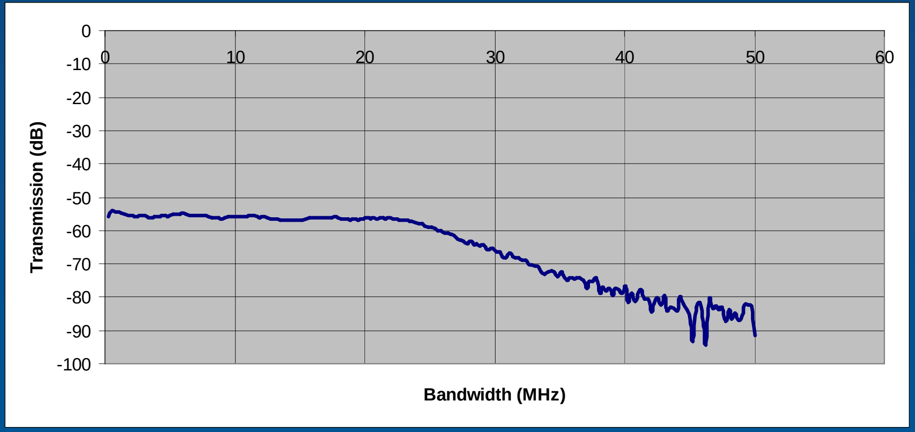
> **Pre-equalization: Resonant driving circuit**



A single resonant driving circuit



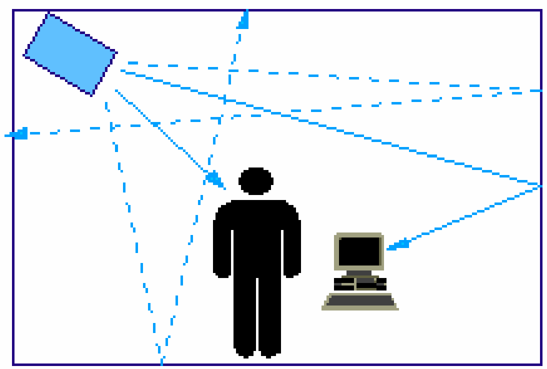
Multiple resonant points (normalized)



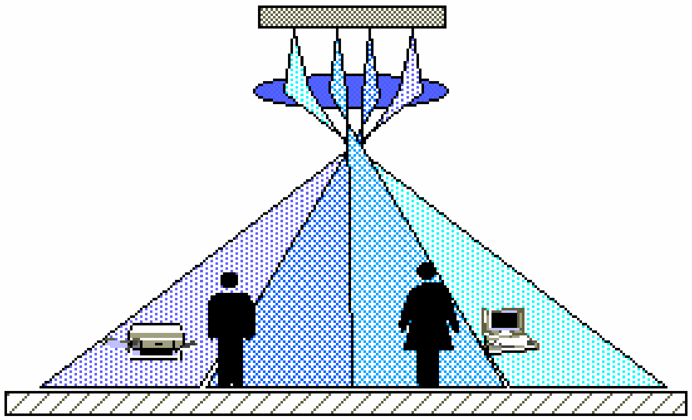
Bandwidth of 16 LED source

Channel modelling

- Two propagation paths:
- Line of sight (LOS): strong paths calculated using the illumination patterns from LED arrays
- Diffuse: modelled by assuming the room is equivalent to an integrating sphere
- Channel impulse response is calculated for each point in the room

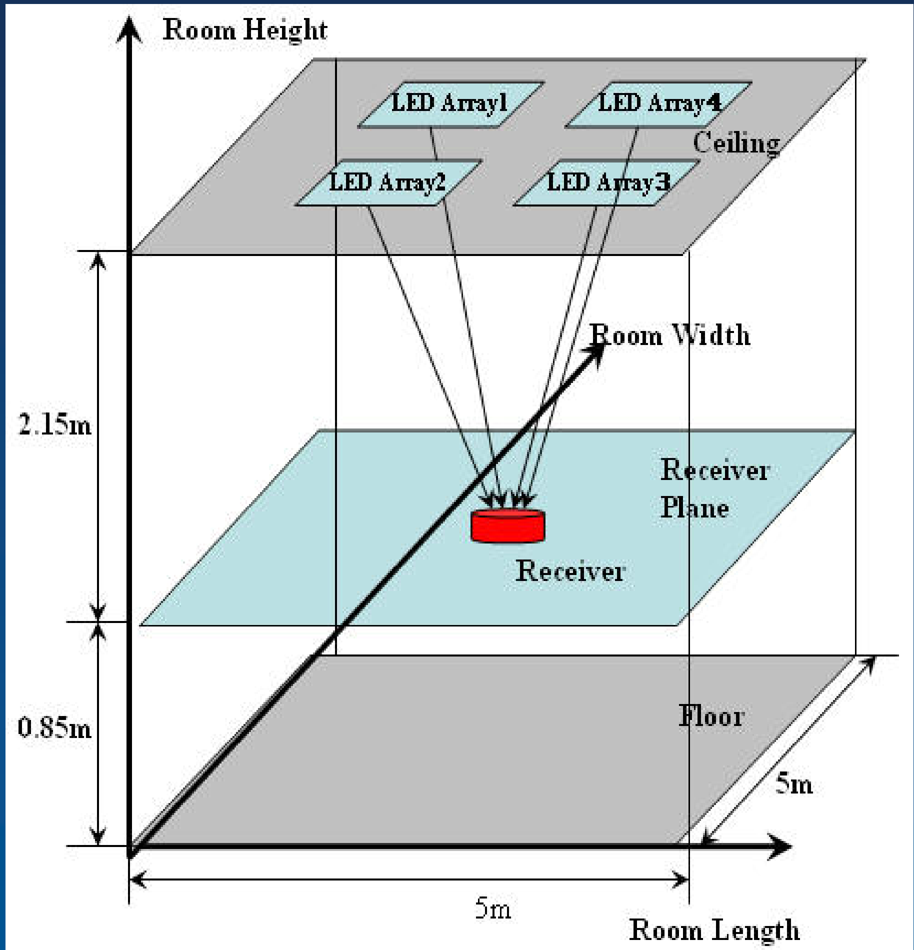


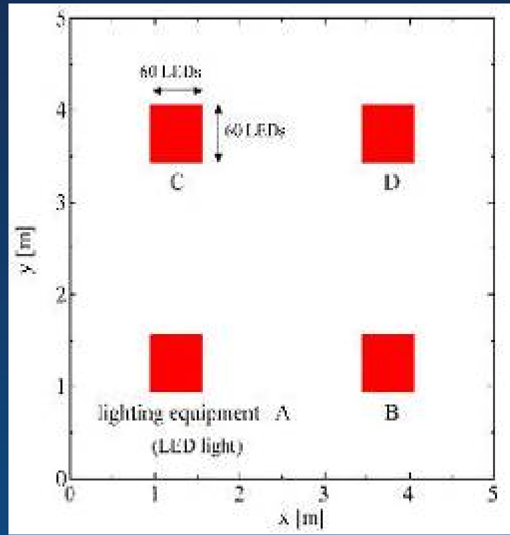
Diffuse channels

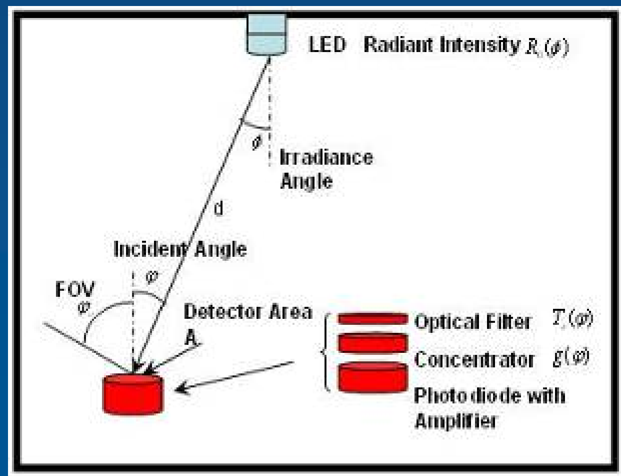


Line of sight channels

VLC modelling

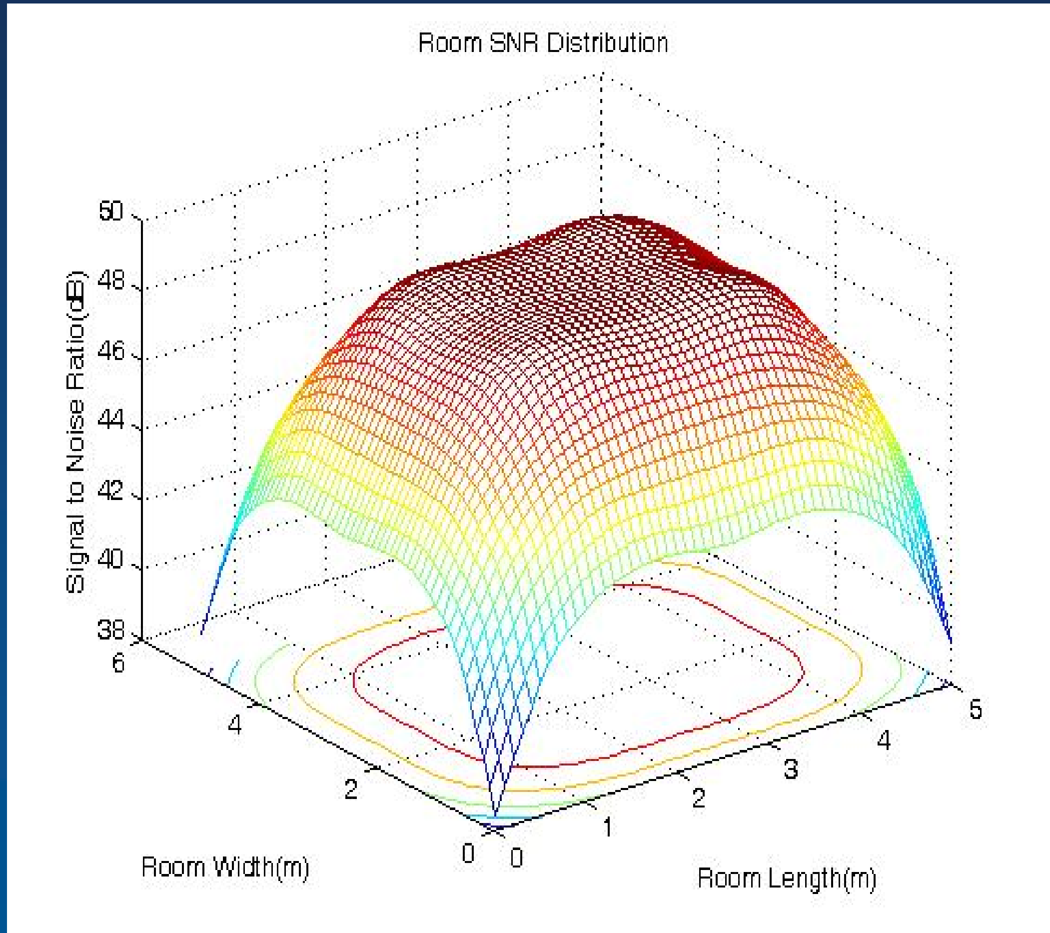






Room Power Distribution

- Assume
  - 1% modulation of typical illumination power
  - Typical receiver performance
- Conclusions
  - Very high SNR available
    - SNRmin = 38.50dB
    - SNRmax = 49.41dB
  - Modulation limited by source bandwidth

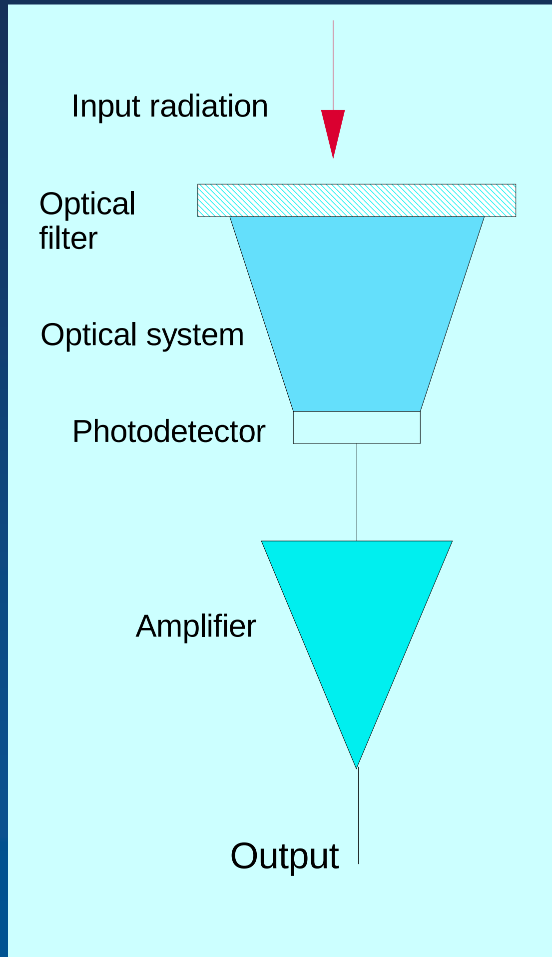


Noise sources

- Optical noise
  - Daylight
    - Generates DC photocurrent
      - Blocked at receiver due to AC coupling
      - Creates shot noise
  - Other optical sources
    - Fluorescent, Incandescent
      - Creates electrical interference photocurrent harmonics
  - Mitigated by
    - Optical filtering
      - Wavelength is in band of desired signal
    - Electrical filtering

Optical receiver

- Receiver consists of
  - Optical filter
    - Rejects ‘out-of-band’ ambient illumination noise
  - Lens system or concentrator
    - Collects and focuses radiation
  - Photodetector (or array of detectors)
    - Converts optical *power* to *photocurrent*
      - Incoherent detection
  - Preamplifier (or number of preamplifiers)
    - Determines system noise performance
  - Post-amplifier and subsequent processing

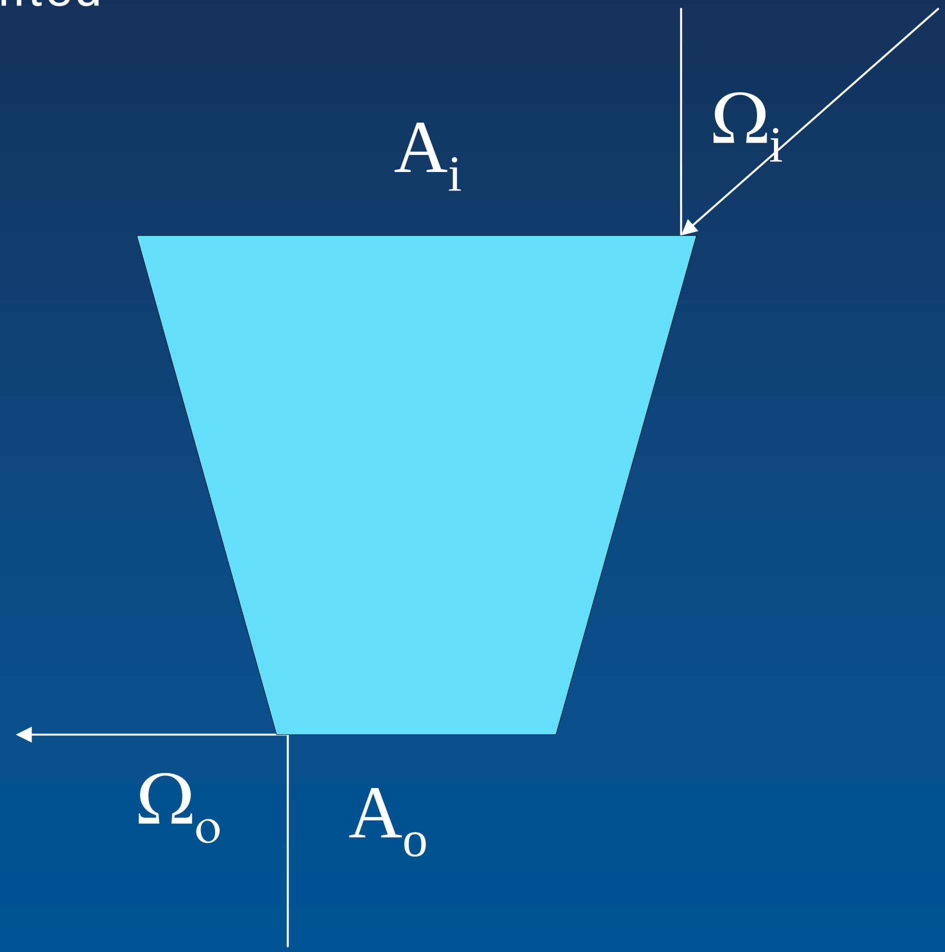


Optical receiver: constant radiance theorem

- Optical ‘gain’ of receiver limited by required field of view

$$A_i\Omega_i <= A_o\Omega_o$$

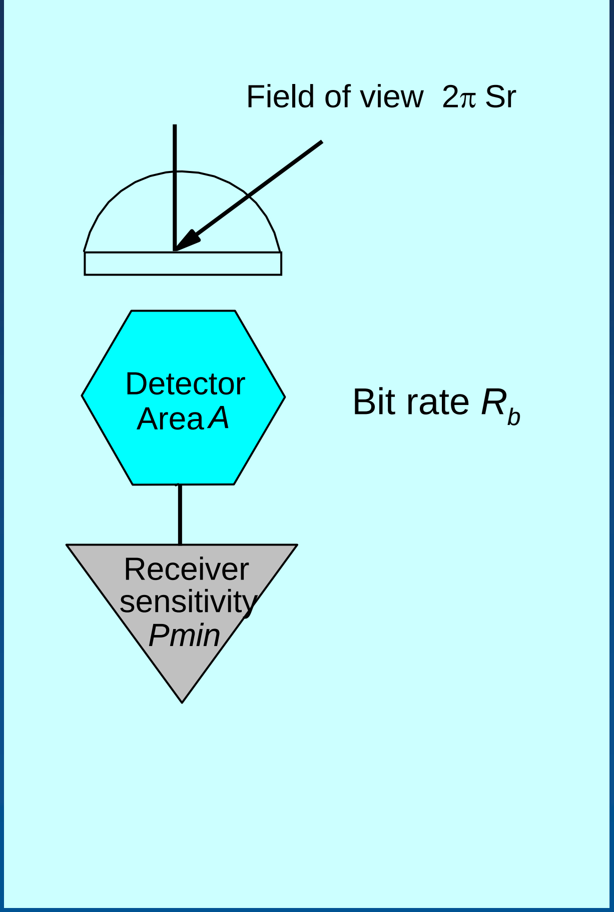
$$A_i\Omega_i <= A_o 2\pi$$



Receiver performance: figure of merit

- Receiver Figure of Merit (FOM)
  - Fibre systems
    - Performance determined by sensitivity (given sufficient detector area)
    - FOV usually not relevant
  - Free space systems
    - Etendue crucial determinant

$$FOM = \frac{2\pi R_b A}{P_{\min}}$$

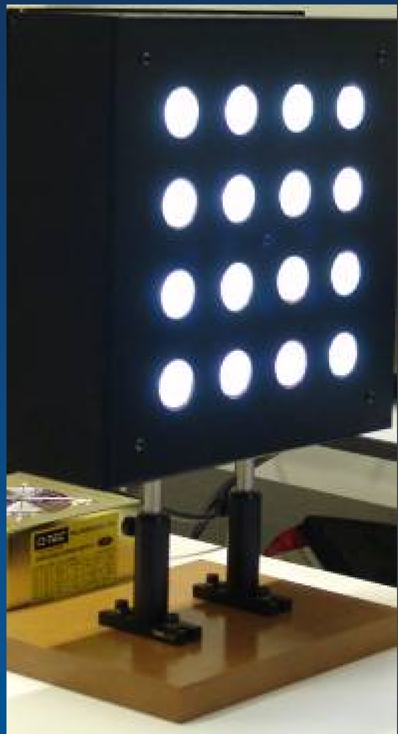


Typical link: components

Transmitter and receiver specifications

Transmitter

- 16 Luxeon LEDs
- P_{ILLUM} = 1.5W
- LED pitch = 60 mm
- I_{DC} = 220 mA
- Mod-index = 0.1
- 45^{o} wide-beam lens
- 7 resonant freq.
- Flat BW of 25 MHz



$2\times R_{illum}$ = 3 m

L_{LOS} = 2 m

Range

L = 2 m

R_{illum} = 1.5 m

R_{comm} = 0.5 m

Receiver

- Concentration lens

  D = 50mm

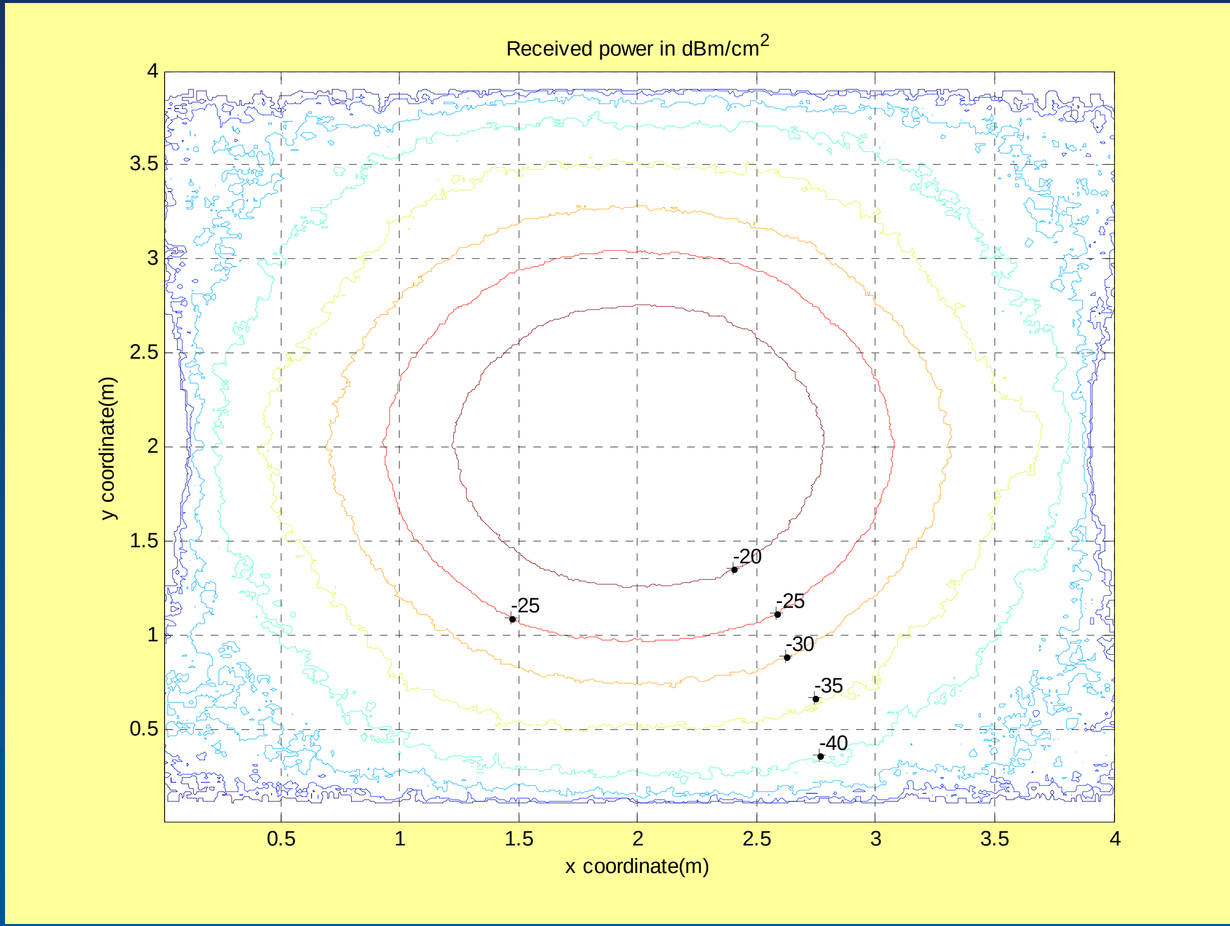
  F = 60mm
- Detection area

  35 mm^{2}
- Pre-Amp
- Post-Amp

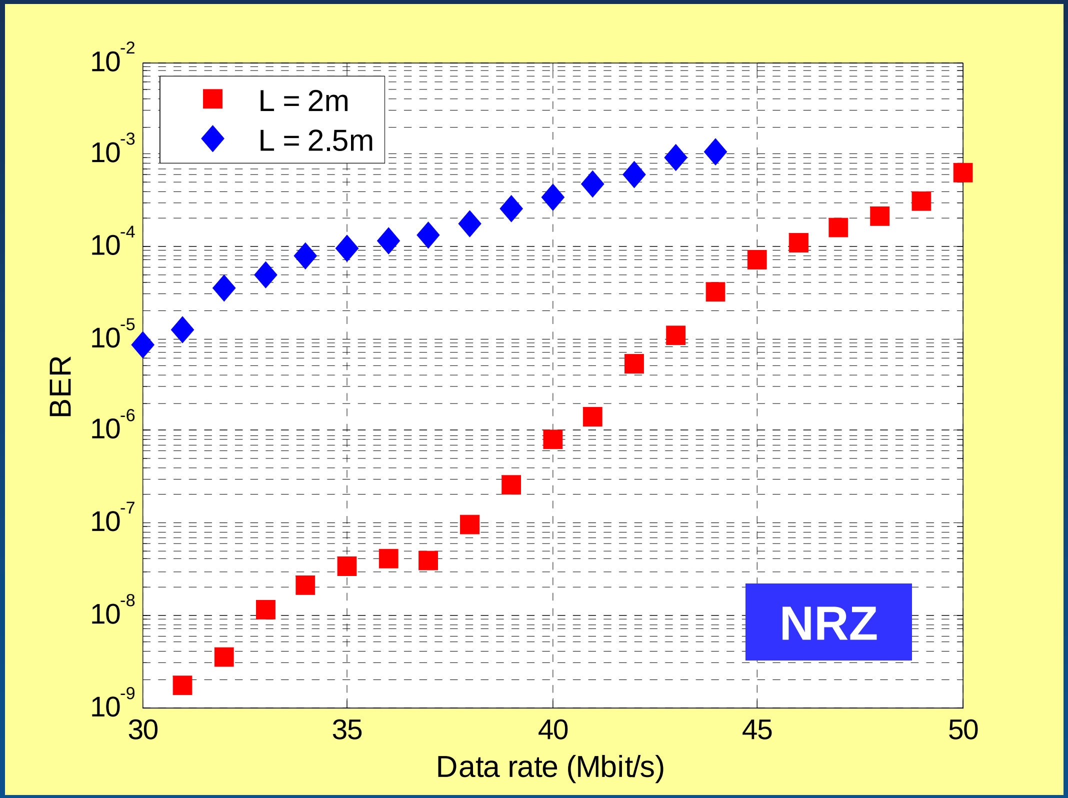
  (ampl. limiting)

Typical link: illumination

Power distribution in receiving plane



Typical link: BER performance

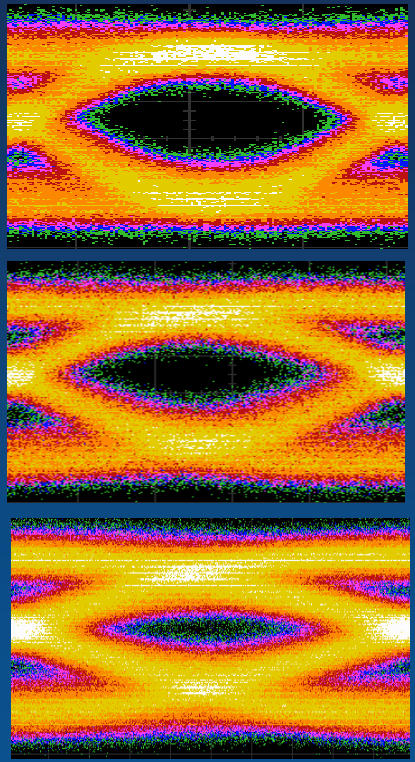


Eye diagram

30 Mb/s

40 Mb/s

50 Mb/s

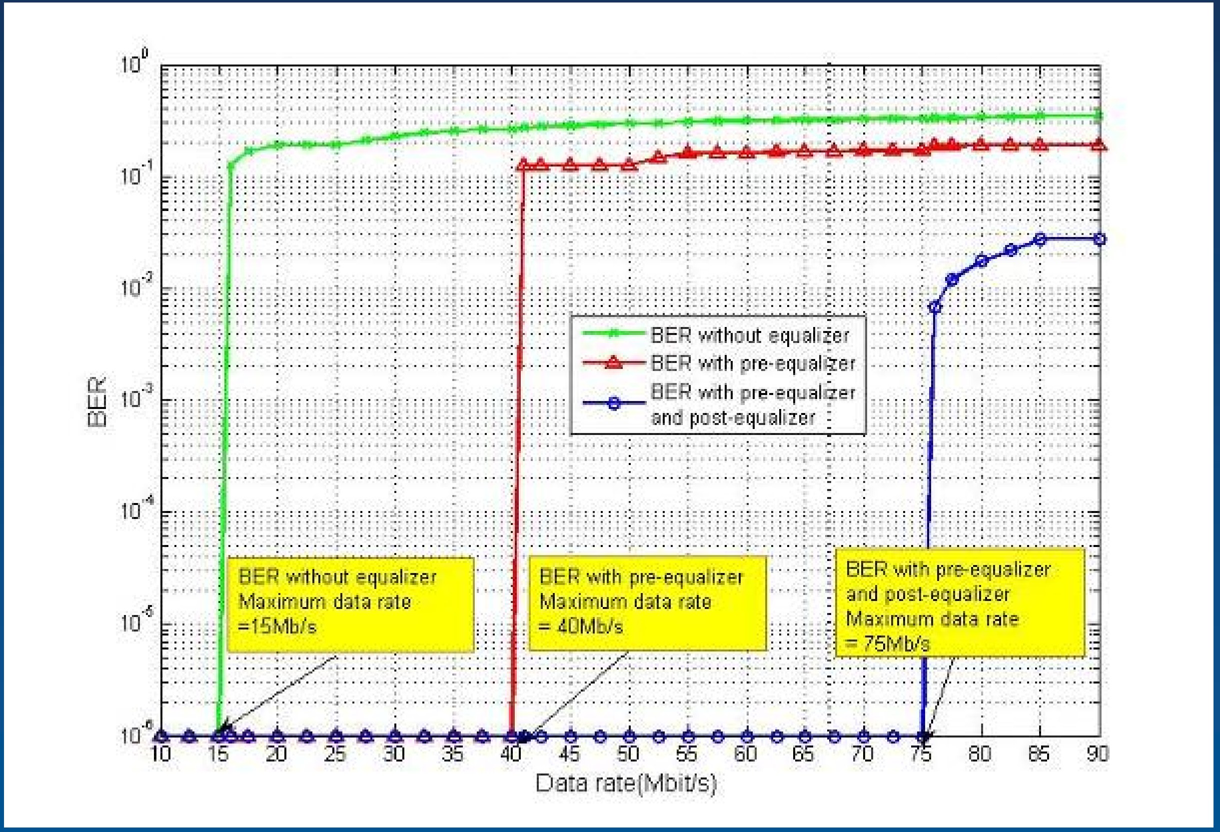


Flat BW ⇒ baseline wandering reduction

- System test in normal lighting condition (room filled with other high-power white light sources)
- Longer distance ⇒ SNR penalty (BER)

Bandwidth improvement: post equalisation

> Pre- and post-equalization: single LED link

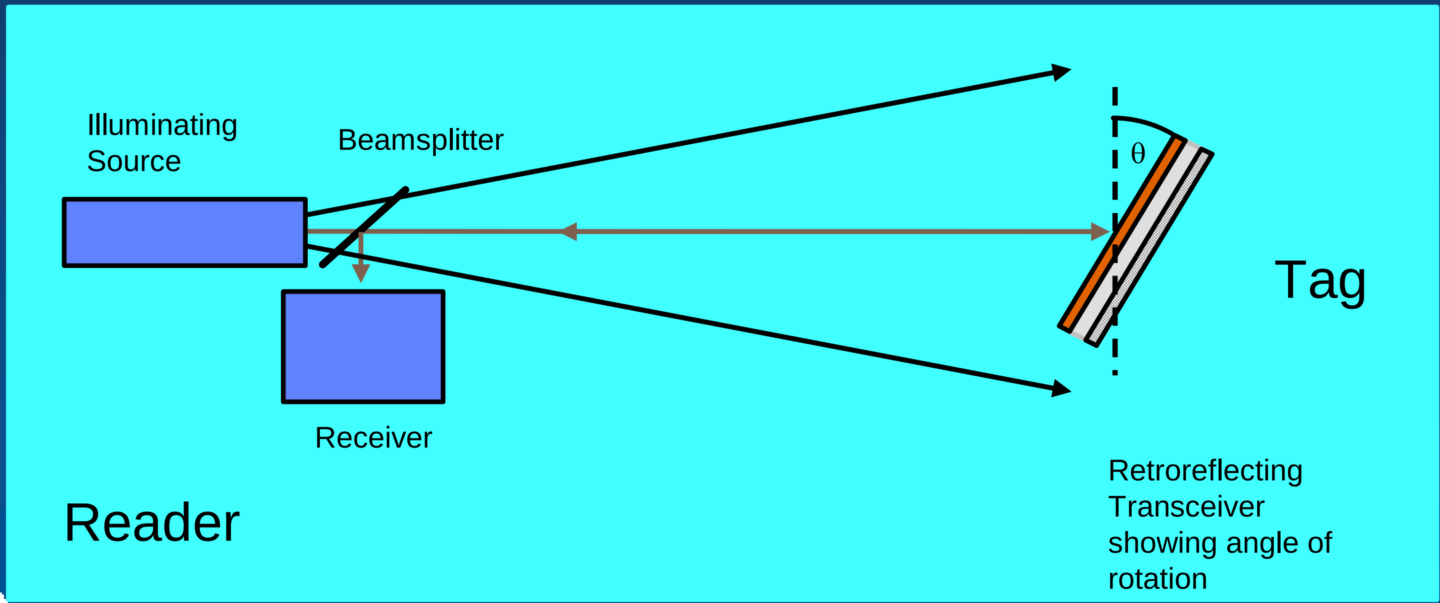


Pre-equalisation: experiment

Post-equalisation: simulation

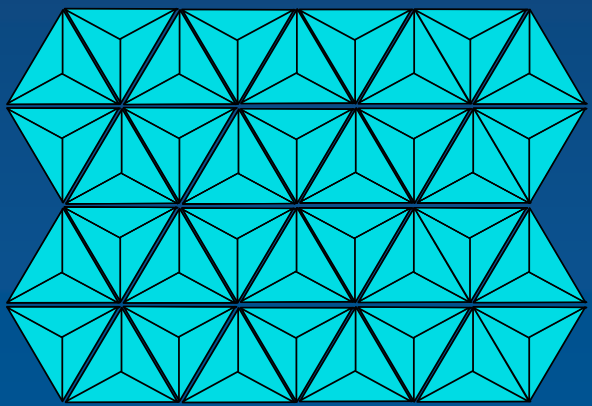
Retro-reflecting link

- Novel optical communications between reader and tag
- Low power (tag has no source)
- Long range (determined by illumination source)
- Visibly secure (user can see beam of light)

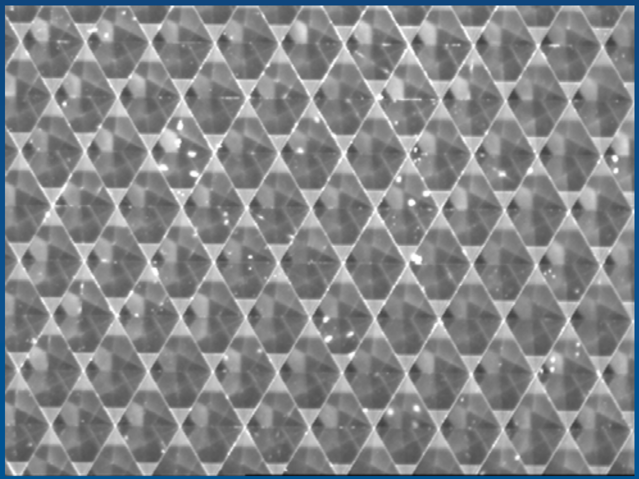


Retro-reflecting link: retro-reflectors

- Front surface reflector array on rigid plastic substrate
- Metallised front face
- Normal incidence reflection loss of 5.5dB (relative to theoretical maximum)
- Returns a polarisation state close to incident for all angles of incidence

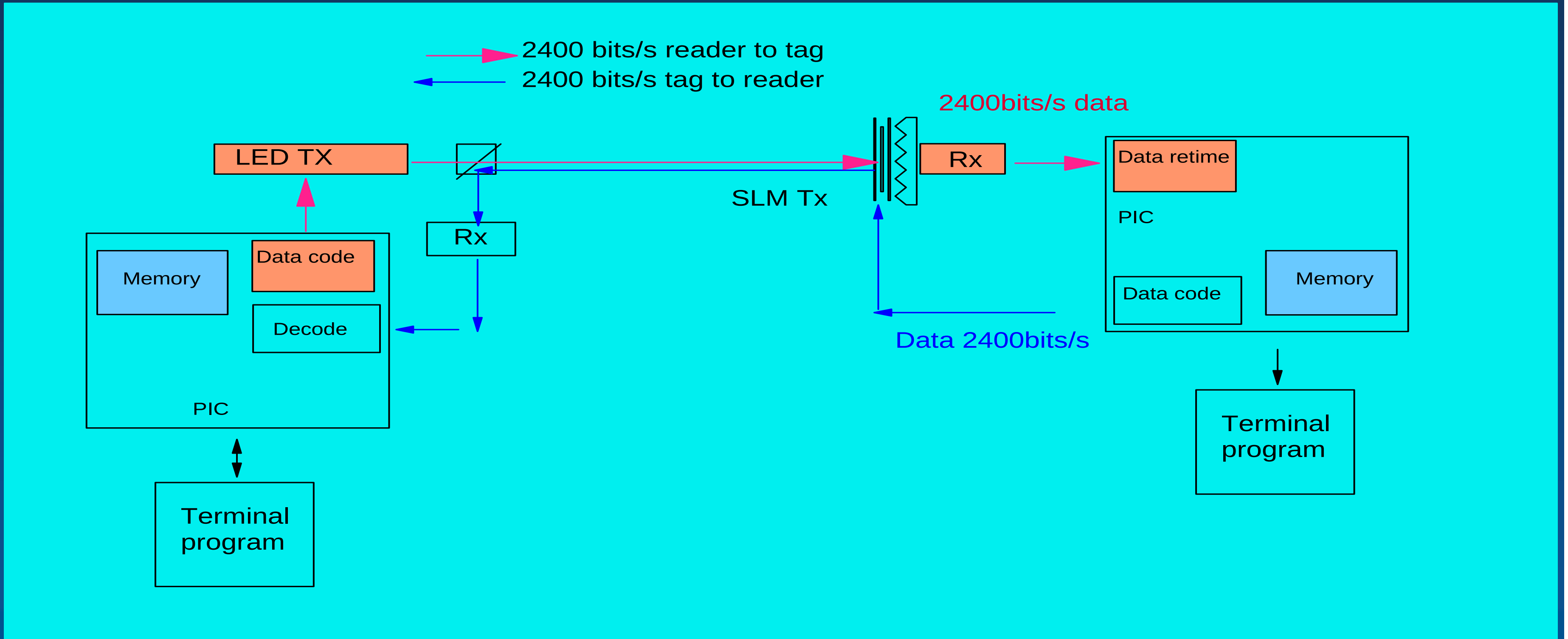


Schematic of retro-reflecting surface



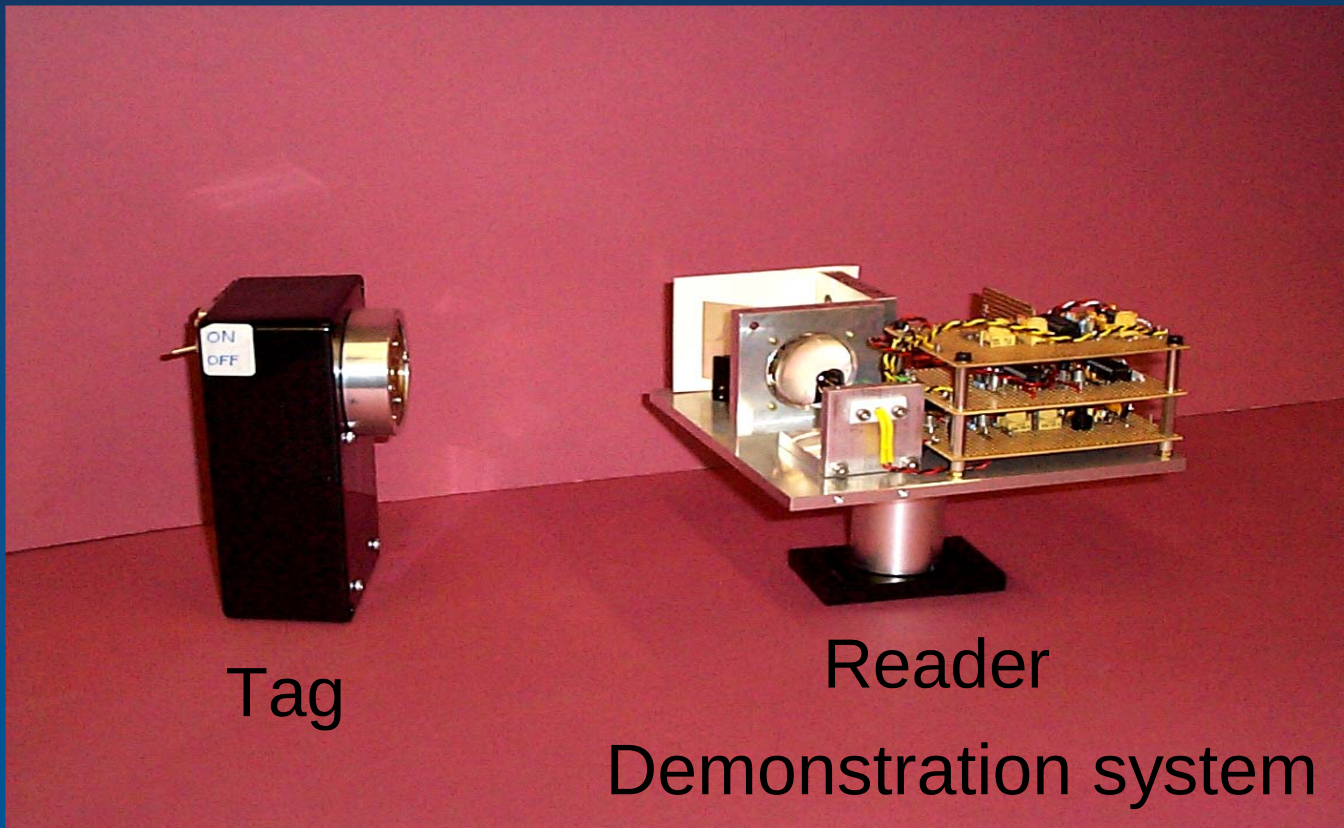
Photograph of surface

Retro-reflecting link demonstration system



Retro-reflecting link demonstration system

- Demonstrator
  - 2.4kb/s bi-directional communication over several metres



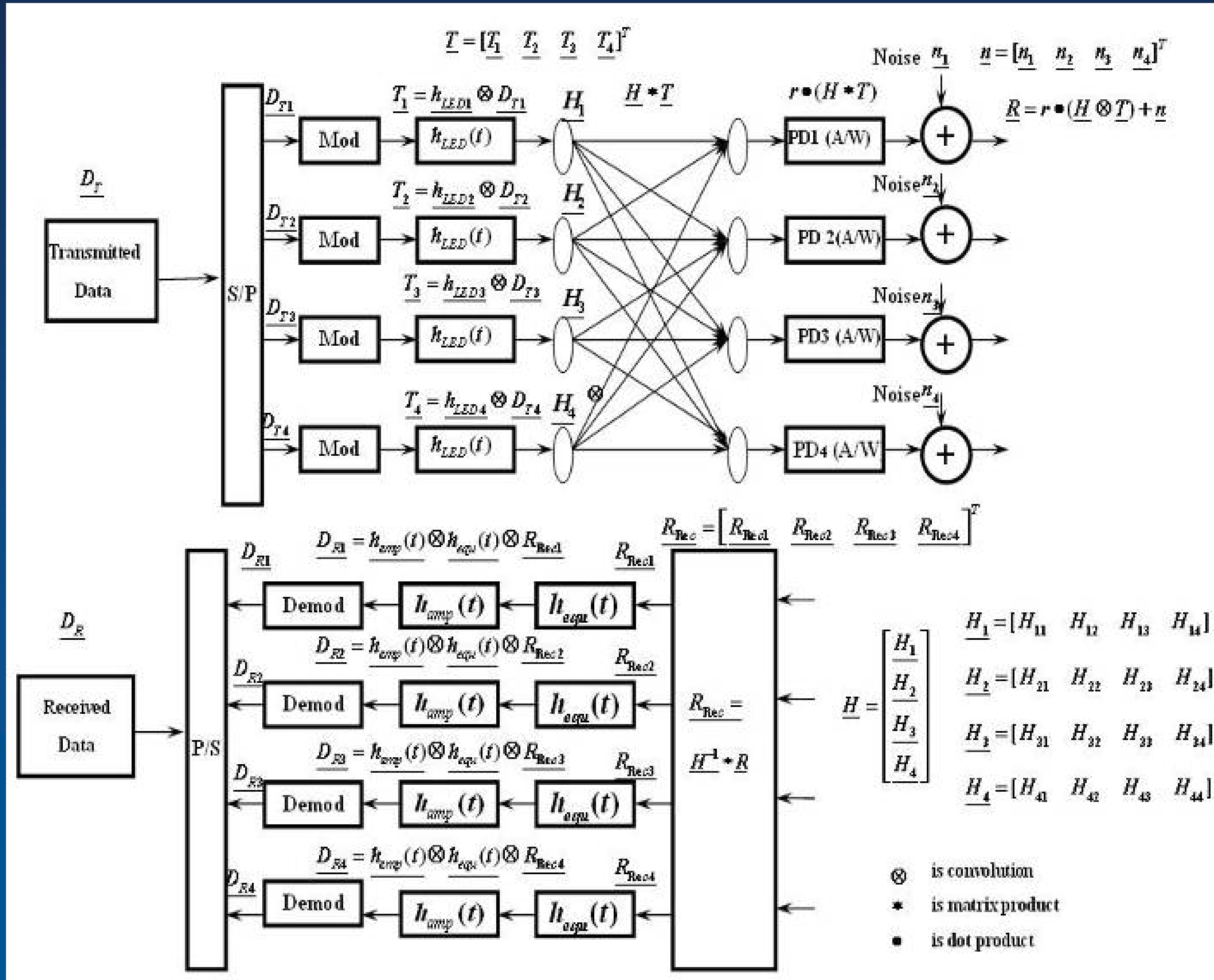
Future developments: optical MIMO

- RF MIMO
- Scattering provides invertible H matrix and decorrelation (capacity gain)
- Difficult to shape radiation pattern with small antenna
- Optical MIMO
- No decorrelation
- Invertible H matrix achieved by system and geometry design
- Simple low-cost elements (lenses) can provide high directivity and/or complex beamshaping

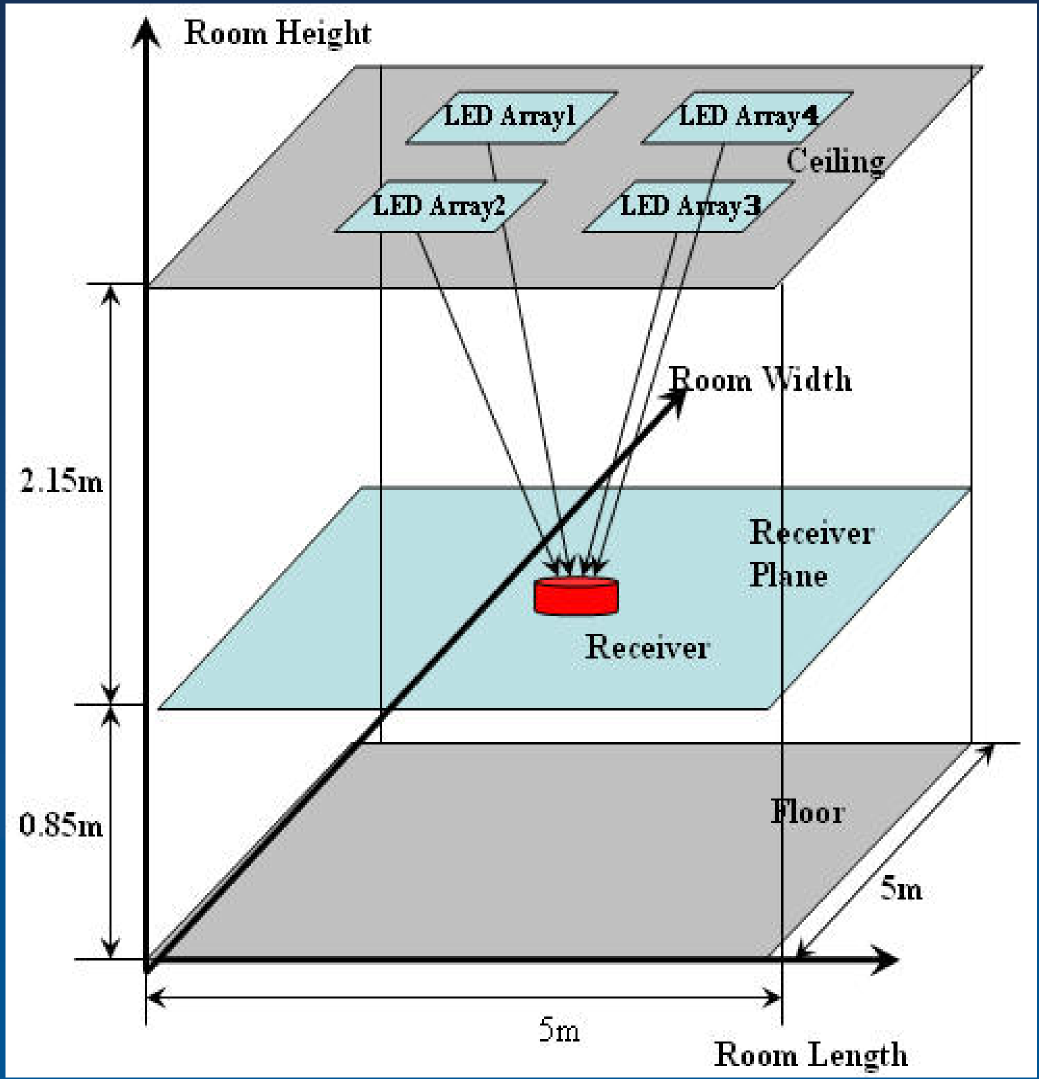
MIMO VLC: simulation Model

Transmitting process

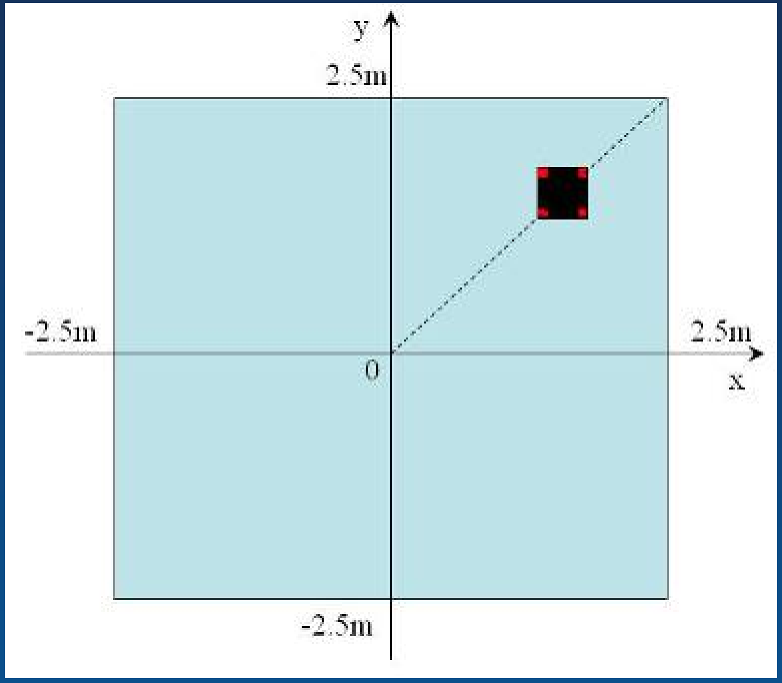
Receiving process



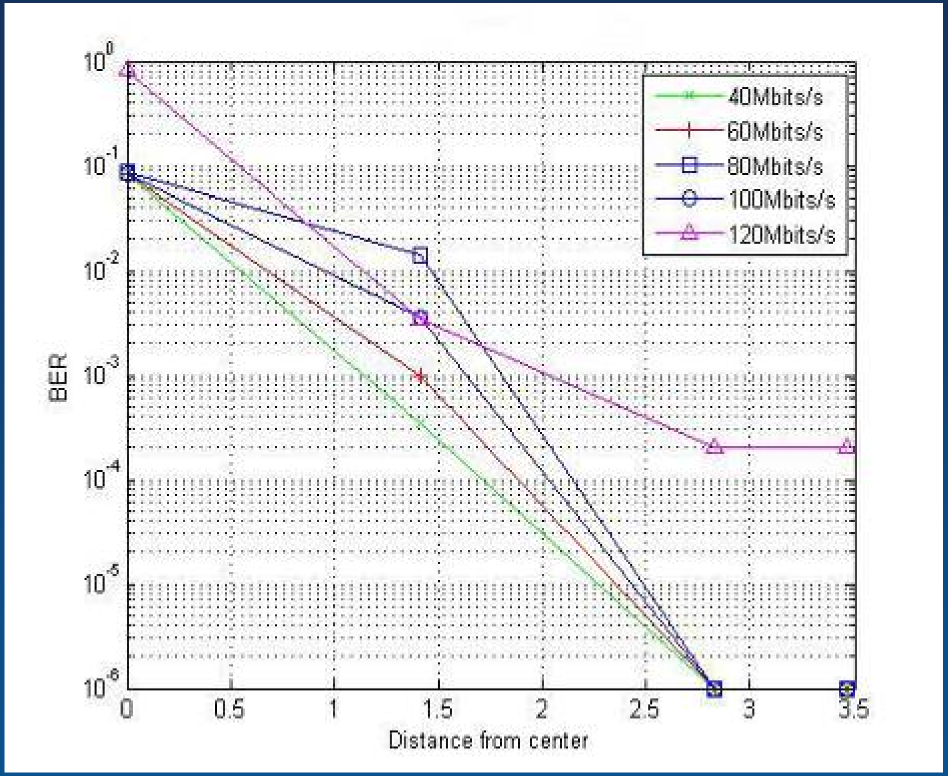
MIMO VLC: simulation system



MIMO VLC: preliminary Results



Position of the receiver



Aggregate data rate is linearly proportional to the number of channels and channel rate

Future technical challenges

- Data rate
  - Equalisation
  - MIMO
  - Complex modulation
- Integration in infrastructure
  - Uplink
    - Retro-reflecting link
  - RF/VLC integration

Conclusions

- VLC offers
  - High SNR channel
  - Intuitive alignment
  - Visibly secure channel
- Challenges
  - Integration with Wireless infrastructure
  - Higher performance